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Abstract

Greenhouse gas (GHG) emission savings from biofuels dramatically depend upon the source of energy displaced and the effects induced outside the energy sector, for instance land-use changes (LUC). Using consequential life-cycle assessment and including LUC effects, this study provides GHG emission factors (EFs) for bioelectricity, biomethane, and bioethanol produced from twenty-four biomasses (from dedicated crops to residues of different origin) under a fossil and a non-fossil energy system. Accounting for numerous variations in the pathways, a total of 554 GHG EFs were quantified. The results showed that, important GHG savings were obtained with residues and seaweed, both under fossil and non-fossil energy systems. For high-yield perennial crops (e.g. willow and *Miscanthus*), GHG savings were achieved only under fossil energy systems. Biofuels from annual crops and residues that are today used in the feed sector should be discouraged, as LUC GHG emissions exceeded any GHG savings from displacing conventional energy sources.

Key words: Biofuels; Land-use changes; GHG emission factors; biomass; waste.

1. Introduction

In an endeavour to limit the World temperature increases, there is a growing focus on reducing the greenhouse gas (GHG) emissions from the energy sector, this accounting for ca. 65% of the global GHG emissions (Herzog, 2009). Among others, a lot of attention has been paid on bioenergy. Early life-cycle assessments (LCAs) of bioenergy scenarios (up to about 2008) found a significant net reduction in GHG emissions when bioenergy replaces fossil energy (Cherubini and Strømman, 2011). However, later assessments including potential carbon leakages triggered by competition for land, inverted the conclusions of those earlier studies, or alternatively, showed dramatically reduced GHG savings from biofuels. Essentially, it is argued that an increased demand for crop (or substrates currently used in the feed sector) would trigger an increased demand for land, ultimately fulfilled through arable land expansion and intensification of current production (Searchinger et al., 2008; Marelli et al., 2011; Edwards, et al., 2010; Fargione et al., 2008; Tonini et al., 2012; Hamelin et al., 2014). Such effects are commonly referred to as indirect land-use changes (iLUC) and represent a significant source of CO_2 emission.

The “well-to-tank” study of Edwards et al. (2013) established, using consequential LCA, GHG emission factors (EFs) for a large number of biofuel pathways based on wheat, sugar beet, sugarcane, palm, rapeseed, and residuals such as municipal organic waste, manure, wood, cooking oil, and straw. Though it is well acknowledged as a landmark, the study of Edwards et al. (2013) does not include impacts from LUC. These, which for example include the savings associated with displaced feed-products, would likely have a tremendous influence on the results, as illustrated in Tonini et al. (2015) for a variety of such feed displacements. In another comprehensive bioenergy study, Wenzel et al. (2014) studied 16 biomass conversion pathways to electricity, heat and transport under several future framework conditions, including systems with 100% renewable energy. The study of Wenzel et al. (2014) focused on a more limited number of substrates (manure, straw and woody biomass including residues from forestry management, energy plantation and punctual harvest from existing forest), but included iLUC. It showed the importance of accounting for iLUC; for example, the average EF for an eucalyptus plantation on a tropical grassland passed from a net carbon sink (-15 g CO_2 MJ_{wood}^{-1}) to a net carbon emitter when the iLUC was included (up to 83 g CO_2 MJ_{wood}^{-1}). A more detailed comparison between the results of Edwards et al. (2013), Wenzel et al. (2014) and the present study is presented later.

There is, thus, still a need to supply decision and policy makers with clear and easy-to-use EFs reflecting the net GHG emissions of key biomass conversion pathways, including all the consequences involved over the whole system. In the attempt to do precisely this, the aim of this study is to quantify GHG EFs for bioelectricity, biomethane and bioethanol produced from twenty-four individual biomasses, encompassing a wide range of substrates from dedicated energy crops to wastes and residues of different origin. This was done by applying consequential life- cycle assessment consistently to all the considered biomass substrates and pathways. The benefits derived from the use of co-products (e.g. heat, feed, fertilizers, other biorefinery co-products) generated along with the "main" biofuel were included by applying system expansion, and so were the impacts from iLUC. The GHG EFs are provided with respect to: i) a fossil energy system (representing a short-term, here assumed for the period 2015-2030) relying on conventional fossil fuels (e.g. coal, natural gas, and gasoline) and ii) a non-fossil energy system (representing a long-term, here assumed for the period 2030-2050) running on renewable energy sources (wind and biofuels).

2. Materials and methods

2.1 Goal, scope, and functional unit

The assessment was performed following the ISO standards for LCA (14044, 2006; ISO 14040, 2006). In LCA, two main alternative approaches can be distinguished: attributional and consequential (Finnveden et al., 2009), the latter also being referred to as a change-oriented approach. In this study, a consequential approach was adopted, this being acknowledged as the most suitable to support decision-making processes (Weidema, 2003).

As illustrated in Figure 1, three different individual services (corresponding to three individual functional units) were considered: production of i) 1 kWh bioelectricity (ex-plant), ii) 1 MJ biomethane (95% methane), and iii) 1 MJ bioethanol (99.7% bioethanol). Each service can be provided by different combinations of technology pathways. Similarly, different alternatives for the use of the co-products generated within the conversion processes were investigated (Figure 1). For example, bioelectricity can be produced through: combustion-CHP (combined heat and power; Bel1); gasification with further combustion of the syngas in CHP-gas engines (Bel2);~~,~~ or anaerobic digestion with further combustion of the biogas in CHP-gas engines (Bel 3/4, depending on whether the recovered solid fraction from the digestate is combusted or gasified).

The assessment considered two distinct energy systems (fossil and non-fossil; see section 2.4). For this, a short- and long-term temporal scope was considered, i.e. the marginal suppliers and displaced alternatives were identified based on today's situation and a situation with a fully renewable energy system, respectively. The geographical scope was Denmark, i.e., the inventory data for biomass composition, technologies, crops, and the legislative context were specific to Danish/North European conditions.

GHG emissions (100y horizon) were quantified with IPCC 2007 (Forster et al., 2007). Background LCA data were obtained from the Ecoinvent v3.1 consequential database (Ecoinvent Centre, 2015). Impacts associated with capital goods were excluded due to lack of data.

2.2 Biomass substrates

The biomass substrates considered in this study were: i) aquatic crops (seaweed, as *luminaria digitata*), ii) perennial energy crops (*Miscanthus*, willow, ryegrass), iii) annual energy crops (sugar beet, maize, wheat, barley), iv) agro-industrial residues (brewer's grain, beet tops, beet pulp, potato pulp, beet molasses, whey) and v) other residues (household food waste, wood residues, pig, cow, chicken manure, wheat straw, maize stover, sewage sludge, wild grass currently left unharvested). In total, twenty-four biomass substrates, key in the North European context, were considered.

2.3 Alternative (counterfactual) management of the biomass substrates

Most biomasses, even when "residual" of other activities, are currently in use. Therefore, accounting for the effects of diverting them from their current use/function to bioenergy production is fundamental in order to avoid overestimating (or underestimating) the environmental savings induced in sectors other than the energy's (Tonini et al., 2015; Hamelin et al., 2014). This refers to the so-called "lost opportunity", i.e. what would have otherwise happened with these substrates. The current use/function considered for each biomass is presented in Table 1. The lost opportunity for wild grasses and agro-industrial residues was modelled as described in Tonini et al. (2015), and as described in Hamelin et al. (2011, 2014) for animal manure.

The diversion of household food waste, which is currently mostly incinerated in Denmark (ca. 81% of the total, based on national statistics), may induce two main effects: A) the incineration plants will not react and will decrease their energy production correspondingly (i.e. the extra capacity will be decommissioned); or B) the incineration plants will react by importing waste from other EU countries (current situation) as illustrated in Cimpan et al. (2014). As indicated in Table 1, approach B was applied in the baseline, while alternative A was tested in the sensitivity analysis.

With respect to wood residues, decay on-field was assumed as the alternative management following the approach of previous studies (Wenzel et al., 2014; Schmidt and Brandao, 2013).The counterfactual management for sewage sludge was assumed to be mechanical dewatering followed by use on-land (displacing mineral fertilizers), this being the most likely alternative to digestion and/or thermal treatment (Yoshida, 2014). For garden waste, composting followed by use on-land (displacing mineral fertilizers) was considered to be the counterfactual management conformingly with current practice in Denmark (Boldrin, 2009).

For annual and perennial crops, the lost opportunity reflects the alternative use of the land. In this respect, two main modelling approaches exist: A) considering that these crops would be cultivated in place of another (so- called “marginal”) crop. The changed flows of carbon, nitrogen and other substances associated with this effect are also referred to as direct land-use changes, i.e. dLUC (Hamelin et al., 2012). The demand for that displaced feedstock is then met through cultivation somewhere else in the World, leading to indirect LUC (iLUC) effects; B) neglecting the dLUC and only considering the emissions related to the final iLUC effect (expansion and intensification of arable land). This can be justified because the dLUC only includes the displacement occurring in the first place, while all the following displacement-replacement mechanisms are commonly disregarded due to the of information. It may be argued that these may cancel out and/or compensate for the effects of the very first displacement. This study follows the second approach (B), while the first (A) was tested in the sensitivity analysis.

2.4 System boundaries and scenario modelling

The system boundary considered is illustrated in Figure 2 for a generic biomass. It reflects the case of bioethanol production for use in vehicles. The biomass is converted into the main energy service (exemplified by bioethanol). Converting biomass into energy avoids the counterfactual management (for residuals) or implies land-use changes and cultivation (for energy crops). The conversion, besides the main energy service (functional unit), generates co-products that displace conventional products in the market (fertilizers, other energy services, feed).

This cradle-to-gate study includes all life-cycle stages from material extraction/cultivation to the “point of substitution” of the considered energy carriers. This means that, for the scenarios producing electricity as a service, the point of substitution is defined as electricity ex-power plant (1 kWh). For scenarios producing transport fuels, the point of substitution is defined as the energy-input to the vehicle engine (1 MJ), including tailpipe emissions. This also involves that, after this point, the differences in environmental impacts among the bioenergy scenarios are not addressed (due to e.g. transmission/distribution losses and efficiencies of the cars).

The energy co-products generated along with the main energy service (i.e. bioelectricity, biomethane, bioethanol) were considered to substitute marginal fuel extraction and use. In the fossil (short-term, up to 2030) energy system, coal-fired power plants and natural gas boilers were identified as short-term marginal technologies for electricity and heat, respectively, as detailed in Tonini et al. (2015). This is based on the energy policy milestones published by the Danish Government in 2011 (Danish Ministry of Climate, Energy and Buildings, 2011), where phasing-out coal and natural gas is a target for 2030 and 2035, respectively. Similarly, gasoline was considered the marginal fuel for transport, conformingly with the assumptions detailed in Tonini et al. (2015). The GHG EFs for coal-electricity, natural gas-heat and gasoline were taken as 977 g CO_2-eq. kWh^{-1}, 64 and 79 g CO_2-eq. MJ^{-1} (Ecoinvent Centre, 2015).

In the non-fossil long-term, 2030-2050) energy system, the marginal for electricity production was based on wind (GHG EF: 19 g CO_2-eq. kWh^{-1}; Ecoinvent Centre, 2015), as supported by previous studies (Wenzel et al., 2014). Similarly, electric boilers were assumed for heat production (Wenzel et al., 2014), considering conversion efficiencies of electricity to heat of 99% (Danish Energy Agency, 2012). For liquid transport fuels, imported bioethanol (produced from Brazilian sugarcane) was assumed as marginal conformingly with predictions for Denmark (Schmidt and Brandao, 2013) as well as for the whole EU (OECD-FAO, 2013). The GHG EF of bioethanol from Brazilian sugarcane was quantified to 65 g CO_2-eq. MJ^{-1} following the same approach used for the twenty-four biomasses considered in this study.

For animal feed, in both the fossil and non-fossil energy systems, the marginal carbohydrate-feed was assumed to be maize, while for protein-feed, soy meal was considered. These choices are based on detailed elaboration of recent demand trends and future projections (Tonini et al., 2015). The energy content of the feed was modeled in terms of Scandinavian Feed Units (SFU). The GHG EFs for maize, soybean, and palm fruit equaled, respectively, 0.4, 0.38 and 0.1 kg CO_2-eq. kg^{-1} ww.

When considering cultivation of energy crops in countries with high agricultural density, displacement of existing cultivation may occur. In this study, it was considered that the cultivation of energy crops displaces spring barley, conformingly with previous studies (Tonini et al., 2012; Hamelin et al., 2012; Dalgaard et al., 2008; Weidema, 2003) and with predictions from EU authorities (European Commission - Directorate

General Agriculture and Rural Development, 2013). The inventory used for cultivation of spring barley (for the sensitivity case where dLUC is included) as well as all the remaining annual (sugar beet, maize, wheat) and perennial crops (*Miscanthus*, willow and ryegrass) in North European countries was based on Hamelin et al. (2012).

Regarding the treatment of thermal conversion residues, in both energy systems, bottom ashes from biomass combustion were considered to be landfilled, while fly ashes were assumed to be utilized for backfilling of salt mines with negligible environmental impacts (Fruergaard et al., 2010). Treatment of wastewater was not included.

The digestate from anaerobic digestion was assumed, in both energy systems, to replace marginal N, P, and K fertilizers (production and application). These were considered to be urea, diammonium phosphate, and potassium chloride, respectively, based on recent demand trends and expected capacity installations (IFA, 2014). For substrates with high lignin content, it was assumed that the digestate ex-anaerobic digestion was separated into a solid and a liquid fraction (called liquor) following the modelling of Tonini et al. (2015). While the solid fraction was further upgraded to produce a solid biofuel (through dewatering/drying and pelletization) and to recover additional energy, the liquid fraction was assumed to be used on-land as organic fertilizer (for N, P, and K), thus substituting marginal mineral N, P, and K fertilizers.

2.5 Modeling indirect land-use change (iLUC) impacts

The impacts associated with iLUC were included based on the results of Tonini et al. (2015). In this, a deterministic modeling framework was developed and applied in order to quantify the iLUC impacts caused by changes in the demand for arable land. The main assumptions of this model are: i) effects associated with the demand for land are global, given the global nature of agricultural commodity trading; ii) there is a cause-effect relationship between the demand for arable land and expansion/intensification effects; iii) there is full-elasticity of supply (short-term effects on prices and related price-elasticities are not modelled; Weidema et al., 2009).

The model considers that additional crop production is ultimately supplied by: i) net expansion of arable land (25% of the total response) and ii) intensification of current cultivation practices (75% of the total response). The sum of the impacts from (i) and (ii) provides the total iLUC impact. In the model, intensification is considered as 100% input-driven (modeled as increases in N, P and K fertilizers). The detailed iLUC inventory can be found in Tonini et al. (2015).

2.6 Modeling bioenergy conversion

The (bio)chemical energy conversion model developed in Tonini et al. (2015) was applied to quantify all mass/substance/energy flows of each individual bioenergy scenario. The model requires two types of input: i) the (bio)chemical composition of each biomass substrate and ii) technology data such as specific hydrolysis efficiencies, fermentation yields, separation efficiencies, parasitic energy consumptions, energy production efficiencies. The outputs of the model are the mass/energy/chemical composition of the energy carriers (bioethanol, biomethane, syngas, bioelectricity, bioheat, etc.) and of the associated co-products (heat; bioethanol residuals, e.g. molasses, distiller dry grains, stillage, solid fraction; biogas residues, e.g. digestate or solid/liquid fraction from digestate separation; thermal residues, e.g. char, ash; etc.).

For combustion, small-scale combined heat and power (CHP) were considered, as these decentralized units are the most common biomass combustion plants in Northern Europe and have been developed to burn locally available substrates. The net typical efficiencies for such units are, on the basis of the LHV_{ar} (as received at the plant, i.e. after eventual pretreatment of drying and pelletization), 27% and 76% for electricity and heat, respectively (Danish Energy Agency, 2012).

For gasification, a fluidized bed gasifier with cold gas efficiency (CGE, conversion of biomass energy into syngas energy) of 75% was assumed, conformingly with the technology described in Arena et al. (2010). Parasitic electricity consumption equaled 0.075 kWh kg^{-1} input to the system. The produced syngas was assumed to be combusted in gas engines with electricity and heat efficiencies of 45% (on the basis of the energy content of the gas; Danish Energy Agency, 2012).

Anaerobic digestion was modeled as mesophilic digestion with electricity consumption equal to 8% of the electricity produced, while heat consumption was calculated as the energy required to heat the substrates from 8 to 37 ºC. The methane potential was modeled based on the biochemical composition conformingly with the well-known formula from Symons and Buswell (1933). Methane yield was assumed to be 70% of the theoretical potential. Methane fugitive losses from the digesters were assumed to 1% of the produced CH_4, assuming implementation of best available technologies. The produced biogas was assumed to be combusted in gas engines with the same efficiencies as for syngas. Air emissions following the combustion of the biomass and of the bio/syngas were based on specific Danish data (Nielsen et al., 2010).

Bioethanol production was modelled following the approach of Tonini et al. (2015). It was assumed to occur from C6-sugars hydrolyzed from cellulose. Non-hydrolyzed and unconverted sugars (both C5 and C6), along with unconverted lipids, proteins, and lignin were routed to a mixed residual stream. This, if the input-biomass was rich in lignin, was later separated into a solid (lignin-rich) fraction and a residual

(C5-rich) liquid fraction by centrifuging. The solid fraction was assumed to be further heat-dried to 90% DM and pelletized for energy use in gasification or combustion plants.

The emissions following the use on-land of digestates (organic residues) from anaerobic digestion were modelled as in Tonini et al. (2015); direct N_2O-N: 1.5% of the N applied with the digestate; NH_3-N: 11% of the N in the digestate; NO_x-N: 1.1% of the N in the digestate; NO_3-N: 51% of the digestate-N content; and the indirect N_2O-N was quantified based on IPCC (De Klein et al., 2006).

2.7 Sensitivity and uncertainty analysis

Sensitivity and uncertainty analyses were addressed at two levels: i) scenario uncertainties and ii) parameter uncertainties, conformingly with the approach suggested in Clavreul et al. (2012). Scenario uncertainties were addressed by: I) assessing the performance of the bioenergy scenarios with two opposite energy systems (fossil/non-fossil). This is discussed in results section. II) Assessing the influence of utilizing only 50% of the nominal heat produced at the CHP plants. III) Assessing the impact of considering dLUC (approach A vs. B, as described in section 2.3). IV) Assessing the consequences of diverting household food waste away from incineration plants (approach A vs. B, as described in section 2.3).

Parameter uncertainties were addressed by assigning mean value and standard deviation to the parameters used as input to the model, assuming normal distributions. All scenarios were modeled using Monte Carlo analysis (1000 simulations).

3. Results and discussion

The GHG EFs related to producing bioelectricity (scenarios namely Bel), biomethane (scenarios namely BM), and bioethanol (scenarios namely BE) from the twenty-four substrates are displayed in Figure 3a-c for the fossil and in Figure 3d-f for the non-fossil system. A total of 554 GHG EFs are displayed. The difference between the fossil- and non-fossil system stems from the impacts/savings associated with using/displacing the marginal energy sources (coal/natural gas/gasoline vs. wind/biofuel). For example, bioheat produced from the biomass substitutes natural gas-based heat in the fossil system (short-term) and wind-based heat in the non-fossil (long-term), as detailed in section 2.4. For the purpose of comparison, the GHG EF of the reference marginal energy (coal/gasoline/wind/bioethanol) used to provide the same energy service is also displayed in Figure 3. It should be noted that, for household food waste, combustion (Bel1) is not shown as it represents the reference counterfactual management for this scenario (Table 1). Figure 4a-c and Figure 4d-f illustrate the breakdown of the GHG emissions for selected bioenergy pathways. Net impacts/savings for the individual bioenergy scenarios were obtained by subtracting the avoided impacts (negative values in the charts) from the induced impacts (positive values).

3.1 Production of bioelectricity

In a fossil energy system (Figure 3a), residues from all origins (urban, agriculture, forest) highlighted the lowest GHG EFs, showing significant GHG savings compared with conventional fossil sources of production. As an example, the GHG EF of bioelectricity from digestion of pig/cow manures was between -395 and -128 g CO_2-eq. kWh^{-1}, and the GHG EF of bioelectricity from digestion of household food waste ranged from -279 to -145 g CO_2-eq. kWh^{-1}. The negative values reflect the importance of the effects induced outside the energy sector by avoiding conventional management of these substrates, i.e. conventional storage (without treatment) for manure and landfilling for imported waste from the EU. For the latter, the EFs also accounted for the additional electricity and heat benefits derived from utilizing the imported waste to supply the missing capacity at the incineration plants (as food waste is diverted to anaerobic digesters). This simply shows that the opportunity cost of utilizing these substrates for bioenergy is, from a GHG mitigation perspective, highly favorable under the current fossil energy system and biomass management practices. This was generally true for wheat straw and maize stover, where the benefits derived from energy recovery and displacement of fossil fuels exceeded the impacts from carbon and nutrient losses on-field. Though involving demand for arable land, thus inducing effects in the form of iLUC (Figure 4a) perennial crops also showed considerable GHG savings in the bioelectricity scenarios when the marginal energy source was coal (Figure 3a). Annual crops, with the exception of maize and to some extent sugar beet, showed GHG EF comparable to coal-electricity for a number of bioelectricity pathways. For all the studied pathways, the GHG EF of barley was always higher than that of coal-electricity. This was due to its lower yield on field compared with the other energy crops and thus higher iLUC impact (Figure 3a). Similarly to annual crops, food-industry residues showed GHG EFs higher than those of conventional fossil fuels, under the assumption that these substrates would be otherwise utilized in the feed market. Their induced effects, corresponding to iLUC and cultivation of feed-crops (Figure 3a), reflect their high nutritional value and, thus, the lost opportunity of not using them as feed. If these were not be used for feeding under business-as-usual conditions, the impact associated with iLUC would become null and their performance would be comparable to urban and agricultural residues/waste.

From Figure 3d it is evident that in a non-fossil energy system, based on wind energy as the marginal supplier, only manures and some residues (sewage sludge, garden waste, maize stover, wheat straw, and wood residues) are appealing from a GHG reduction perspective. This was mainly a consequence of the magnitude of the induced effects (i.e. benefits from avoiding current management), as the credits from displacement of marginal energy production (being now wind) became significantly lower compared with the figures of the fossil energy system.

Focusing on the conversion to bioelectricity, thermal combustion (Bel1 and Bel2) appeared, as expected, to be the best conversion path for substrates with low water content (chicken manure, straw, stover, wood residues, willow, *Miscanthus*). On the other hand, anaerobic digestion (Bel3 and Bel4) was the best pathway for pig and cow manure, sewage sludge, seaweed, grasses, sugar beet, beet pulp, and potato pulp due to their higher water content and thus higher energy consumption required for separation and drying of the solid fraction in thermal pathways. Combustion generally performed better than gasification, owing to an overall better energy recovery. However, this difference reflects the inventory assumptions related to technologies efficiencies (electricity recovery, cold gas efficiency, etc.). As such, these results should be interpreted bearing in mind the process and technology data assumed.

3.2 Production of biomethane

Similarly to the results shown for bioelectricity, anaerobic digestion with subsequent upgrading of the biogas (BM2 and BM3; Figure 3b) allowed GHG emission savings (compared with conventional gasoline) only for the following substrates: manures (from -104 to 44 g CO_2-eq. MJ^{-1}), household food waste (ranging from -56 to -46 g CO_2-eq. MJ^{-1}), straw/stover (20-50 g CO_2-eq. MJ^{-1}), wild grass (49 g CO_2-eq. MJ^{-1}), seaweed (51 g CO_2-eq. MJ^{-1}) and perennial crops (ryegrass excepted; 10-40 g CO_2-eq. MJ^{-1}). This was, however, not the case when biomethane was produced via gasification with further syngas-upgrading to biomethane (BM1), due to the lower energy conversion efficiency (mainly due to heat consumption) compared with the biological conversion pathway. This trend also applied to the non-fossil energy system where the GHG EF of imported sugarcane bioethanol was comparable to that of gasoline (65 g CO_2-eq. MJ^{-1} vs 79 CO_2-eq. g MJ^{-1}).

Under the fossil energy system, for all the substrates having a significant lignin content (i.e. where a solid fraction could be separated from the liquid fraction after digestion), direct combustion (BM2) and gasification (BM3) of the separated solid fraction showed comparable performances, with direct combustion slightly better owing to an overall higher energy recovery (Figure 3b). This was also the case in the non-fossil energy system (Figure 3e), where the GHG savings associated with the energy produced (from the solid fraction) were dramatically reduced owing to having wind (GHG EF: 19 g CO_2-eq. kWh^{-1}) in place of coal (GHG EF: 977 g CO_2-eq. kWh^{-1}) as marginal electricity supply.

It is remarkable to observe that, in a non-fossil energy system (where wind is assumed to be the marginal supply of electricity), substituting imported transport biofuels (e.g. sugarcane bioethanol) with biomethane generates significantly higher GHG savings than using the same biomass for bioelectricity (this can be seen from Figures 3d and 3e). This is essentially reflecting the higher EF of imported liquid biofuels (and the low EF of wind electricity). This highlights that transport biofuels may represent a sustainability bottleneck when going for 100% renewable energy systems.

3.3 Production of bioethanol

For bioethanol production, under a fossil energy system, only household food waste and agricultural residues (straw and stover) highlighted GHG emission savings compared with conventional gasoline in all pathways (Figure 3c; manure and sewage sludge were not included in these pathways). The GHG EFs ranged from -639 for household food waste to -1 g CO_2-eq. MJ^{-1} for maize stover. Wild grass, seaweed, perennial and annual crops (with the exception of barley) resulted in GHG savings only for those pathways where the residual fraction was used for feeding (BE5 and BE6). In this respect, it should be noted that utilizing the C5-sugar rich residual fraction (often referred to as "bioethanol molasses" in the case of straw/stover/lignocellulosic substrates, "stillage" in the case of liquid substrates, e.g. beet molasses, or "distiller dried grains" (DDG) in the case of grains) for feeding was always preferable to the remaining alternatives (i.e. BE5-6 was always better than BE1-4; Figure 3c). The reason for this was, once more, the GHG savings induced outside the energy system. These related to displacing marginal carbohydrate-feed, i.e. maize, and to avoiding corresponding land-use changes, as the land would no longer be demanded for such cultivation.

GHG savings were similar under the non-fossil energy system (Figure 3f) as the GHG EF of sugarcane bioethanol was comparable to gasoline. Production of bioethanol from perennial energy crops (e.g. willow and *Miscanthus*) could also be justified from a mere GHG perspective, owing to the high crop yield achievable and correspondingly low iLUC, finally leading to GHG EFs ranging from 60 to 100 g CO_2-eq. MJ^{-1}, which is comparable to the GHG EF of imported sugarcane bioethanol.

3.4 Sensitivity and uncertainty analysis

When heat utilization equaled 50% of the nominal heat recovery at the plant, the GHG EFs were increased compared with the baseline due to the decreased energy system efficiency. In a few cases involving ryegrass and *Miscanthus*, however, this change led to a shift of the results towards higher GHG EFs than that of the reference marginal fuel (i.e. coal).

Including the dLUC impacts of the displaced spring barley cultivation (approach A, see section 2.3) did not change significantly the results compared with the baseline, with the exception of the results for sugar beet (all conversion pathways). For this, the inclusion of dLUC credited the bioenergy scenarios with additional GHG savings due to the high crop yield and low GHG emissions for cultivation compared with the marginal crop (spring barley). In none of the remaining scenarios, though including dLUC did induce higher GHG emissions, there was an actual shift of the total GHG EFs towards higher values compared with the GHG EF of the reference marginal fuel. In other words, the two approaches (A and B) led to comparable results.

The assumption on the effects of diverting food waste from incineration is instead crucial to the final results. When assuming that the extra capacity at the incineration plants will not be utilized (i.e. it will be decommissioned; approach A, see section 2.3), under a fossil energy system, producing biomethane or bioethanol from food waste diverted from incineration induced higher GHG EFs than gasoline due to the "lost opportunity" for generating electricity and heat at the incinerators. However, this was not the case under the non-fossil energy system, where producing biomethane (GHG EFs ranging between 51 and 67 g CO_2-eq. MJ^{-1}) was comparable to importing sugarcane bioethanol (65 g CO_2-eq. MJ^{-1}). This simply tells that utilizing household food waste to produce a transport fuel, in place of combustion, may be a better alternative in the long-term when the electricity/heat sectors will run on low-carbon sources (after 2030 according to Danish energy strategies; Danish ministry of Climate, Energy, and Buildings, 2011).

The results of the parameter uncertainty propagation showed that uncertainties may be significant, especially for *Miscanthus*, willow, and ryegrass which highlighted much higher uncertainties compared with the remaining substrates. This was due to the high uncertainty in the crop yield. If this was reduced (e.g. with better information), the uncertainty in the results would decrease correspondingly. Generally, bioethanol and biomethane scenarios highlighted higher uncertainties compared with direct combustion and gasification due to the high intrinsic uncertainty of the conversion process (bioethanol/biomethane potential, practical yield at full-scale, conversion efficiency to heat/electricity, use on-land, etc.). However, except for the case of *Miscanthus*, willow, and ryegrass, none of the remaining individual scenarios displayed an uncertainty that was large enough to change the conclusions of the study.

Keeping these results in mind, the conclusions drawn in this study appeared robust to scenario and parameter uncertainties, with the exception of: i) the assumption regarding the reaction of incinerators to the diversion of household food waste, and ii) the yield of perennial crops. For the first, if the extra-capacity (freed by diverting food waste away from incineration) will be decommissioned, results may be affected under a fossil energy system. Regarding the second, higher/lower yields will significantly improve/worsen the GHG EFs associated with perennial crops.

3.5 Comparison with previous studies

The GHG EFs quantified in this study for bioelectricity and biomethane produced from manures and wood residues are generally in line with the figures obtained by Edwards et al. (2013). For the case of manure, the benefits induced by avoiding conventional management represent a consistent share of the total GHG savings in both studies.

For food waste, both studies highlight GHG EFs much lower than those of conventional fossil fuel. However, the GHG EFs quantified in Edwards et al. (2013) are much higher than in the present. For example, for biomethane production (via digestion) Edwards et al. (2013) quantified about 10-25 g CO_2-eq. MJ^{-1} against -56 to -46 g CO_2-eq. MJ^{-1} of this study. These differences are due to system boundary choices: the greater GHG savings in this study are a consequence of the additional GHG benefits induced by utilizing the extra-capacity available at the Danish incinerators (after diversion of domestic food waste to biogas production) for treating imported EU MSW. This imported waste generates additional electricity and heat delivered to the Danish energy system. Such credits were disregarded in Edwards et al. (2013). However, as illustrated in the sensitivity analysis, the extra-credits included in this study are cancelled out if the extra-capacity at the Danish incinerators is decommissioned.

For bioethanol production, Edwards et al. (2013) quantified GHG EFs between ca. 20 and 40 g CO_2-eq. MJ^{-1} for sugar beet and between ca. 20 and 90 g CO_2-eq. MJ^{-1} for wheat grain. The higher GHG EFs quantified in this study are due to the inclusion of iLUC GHG emissions which dramatically reduce (or cancel off) any saving compared with conventional fossil fuel. The same applies to the case of sugarcane, corn, and barley bioethanol for which Edwards et al. (2013) estimated GHG EFs between 10 and 80 g CO_2-eq. MJ^{-1}, significantly lower than the present study due to disregarding LUC effects.

It should also be noticed that in both studies, the use of biorefinery co-products for feeding appeared preferable to the alternative uses of these.

The study of Wenzel et al. (2014), on the other hand, only focussed on woody feedstock, straw and manure. As opposed to the present study, Wenzel et al. (2014)

considered the electricity of the current energy system to be a mixture of fossil fuels (40%), wind (47%), biomass (11%) and solar (2%). Depending on the biomass source, the EF for electricity in Wenzel et al. (2014) was thus lower (e.g. wood residues) or higher (e.g. eucalyptus from a plantation on tropical forest land) than the coal reference of this study. For bioelectricity, one important difference is that Wenzel et al. (2014) made a distinction on whether the produced power is continuous or flexible (i.e. storable; which was essentially biomethane). In the latter case, the biomethane was always produced from converting all the C in syngas or biogas to methane via methanation, using hydrogen produced from water electrolysis. For this reason, the results of Wenzel et al. (2014) slightly differ with those of the present study. The results of Wenzel et al. (2014) for wood-bioelectricity (-90 to 640 g CO_2-eq. kWh^{-1} for their "current" energy system, depending on the fuel displaced) present a wider range than in this study (-376 to 165 g CO_2-eq. kWh^{-1}). The same applies for the case of future energy systems (60 to 630 g CO_2-eq. kWh^{-1} in Wenzel et al., 2014 versus -156 to 17 g CO_2-eq. kWh^{-1} in this study). It should be noted, however, that the ranges of Wenzel et al. (2014) are due to differences in the type of biomass used/avoided for electricity production, whereas those of this study are due to differences in the technology pathway. The lower end values are smaller in this study, because they consider residual wood only (rather than plantations). The opposite trend, in terms of range breadth, was observed for straw- and manure-based electricity in the current energy system (-905 to -560 g CO_2-eq. kWh^{-1} in Wenzel et al., 2014; -395 to 1000 g CO_2-eq. kWh^{-1} in this study), where this study presents a wider range. The high-end figures of this study reflect the direct combustion of manure, while in Wenzel et al. (2014) manure was first converted to biomethane and not directly combusted. For bioethanol (only from straw in Wenzel et al., 2014), the results of Wenzel et al. (2014) differs with those of this study in the short-term energy system (30 to 130 vs -115 to -33 g CO_2-eq. MJ^{-1} in this study) while they are more similar for the future renewable energy system (-180 to 25 vs -78 to 29 g CO_2-eq. MJ^{-1} in this study).

It should be noted that, on the basis of the results, selected substrates (e.g. annual crops and food-industry residues such as beet residues, whey, brewer's grains) are not favorable for bioenergy production, when assessed individually. However, when considering eventual mixtures with manure (for which bioenergy conversion is, instead, highly favorable), the overall GHG EF of the "mixture" may become lower than that of the reference fossil fuel. This is in accordance with the results of previous studies showing the benefits of avoiding conventional manure management through co-digestion with manure (e.g. Hamelin et al., 2014 and Tonini et al., 2015). Yet, as highlighted in Tonini et al. (2015), the GHG savings of co-digestion may be completely determined by the share of manure itself. In other words, considering *a-priori* a mixture of manure and co-substrate may cloud the impacts/savings associated specifically with the individual biomass substrate. Essentially, all LCA studies highlight that manure digestion is environmentally beneficial compared with conventional storage and direct use on-land. As such, manure digestion should be promoted regardless of the availability of co-substrates.

4. Conclusion

The whole-system GHG EFs of twenty-four biomasses converted to bioelectricity, biomethane, and bioethanol were quantified under a fossil and a non-fossil energy system. Accounting for numerous variations in the pathways and system assumptions, a total of 554 EFs were quantified. Residues and seaweed highlighted important GHG savings both under fossil and non-fossil energy systems. For perennial energy crops, GHG savings were achieved only under fossil energy systems. Bioenergy from annual crops and residues today used in the feed sector should be discouraged as the LUC GHG emissions of these tend to overwhelm the GHG savings from conventional energy sources displacement.

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Supporting Information

Supporting information can be found in the online version of this article.

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Figure captions

Figure 1. Overview of the bioenergy scenarios investigated. Three energy services were considered: I) bioelectricity (scenarios namely Bel), II) biomethane (scenarios namely BM), and III) bioethanol (scenarios namely BE). Different alternative pathways, biological and thermal, to produce these energy services and to utilize the co-products, were considered (namely Bel 1-4, BM 1-3, and BE 1-6; the "main service" provided by the scenario is highlighted in bold, i.e. CHP, CH_4 and BE). CHP: combined heat and power; C6: C6 sugars; Comb: combustion; Res: residual fraction; SF: solid fraction; Syn: syngas.

Figure 2. Illustration of the system boundary of the study for a generic biomass producing bioethanol (as example) for transport. The biomass may be a residue (I) or a dedicated crop (II). Note that the transport biofuel generated does not substitute the corresponding (marginal) transport fuel, as this is used as reference of comparison in the results (Figure 3, 4). The residual fraction can take two distinct routes (A or B). The energy co-products (e.g. heat), generated along with the main energy service, may substitute a fossil or non-fossil energy source depending upon the type of energy system considered (reflecting short- or long-term). For example, heat produced from biomass substitutes natural gas-based heat in the fossil system and wind-based heat in the non-fossil; exp: expansion of arable land on nature; int: intensification of agricultural production.

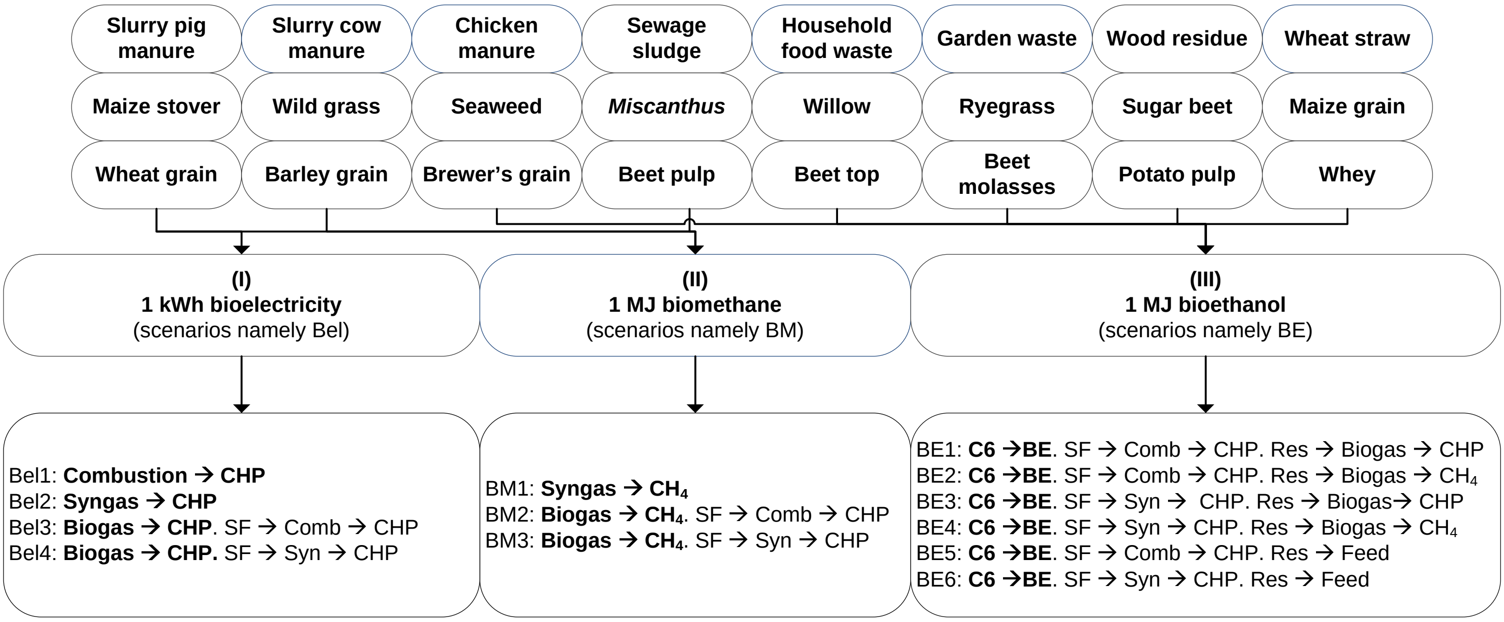
Figure 3. GHG EFs for the production of: bioelectricity (scenarios namely Bel) under a fossil (a) and non-fossil (d) energy system, biomethane (scenarios namely BM) under a fossil (b) and non-fossil (e) energy system, and bioethanol (scenarios namely BE) under a fossil (c) and non-fossil (f) energy system. The marginal fossil fuel (to produce the main energy service, i.e. 1 kWh electricity or 1 MJ transport fuel) is displayed as reference of comparison. CHP: combined heat and power; C6: C6 sugars; Comb: combustion; Res: residual fraction; SF: solid fraction; Syn: syngas.

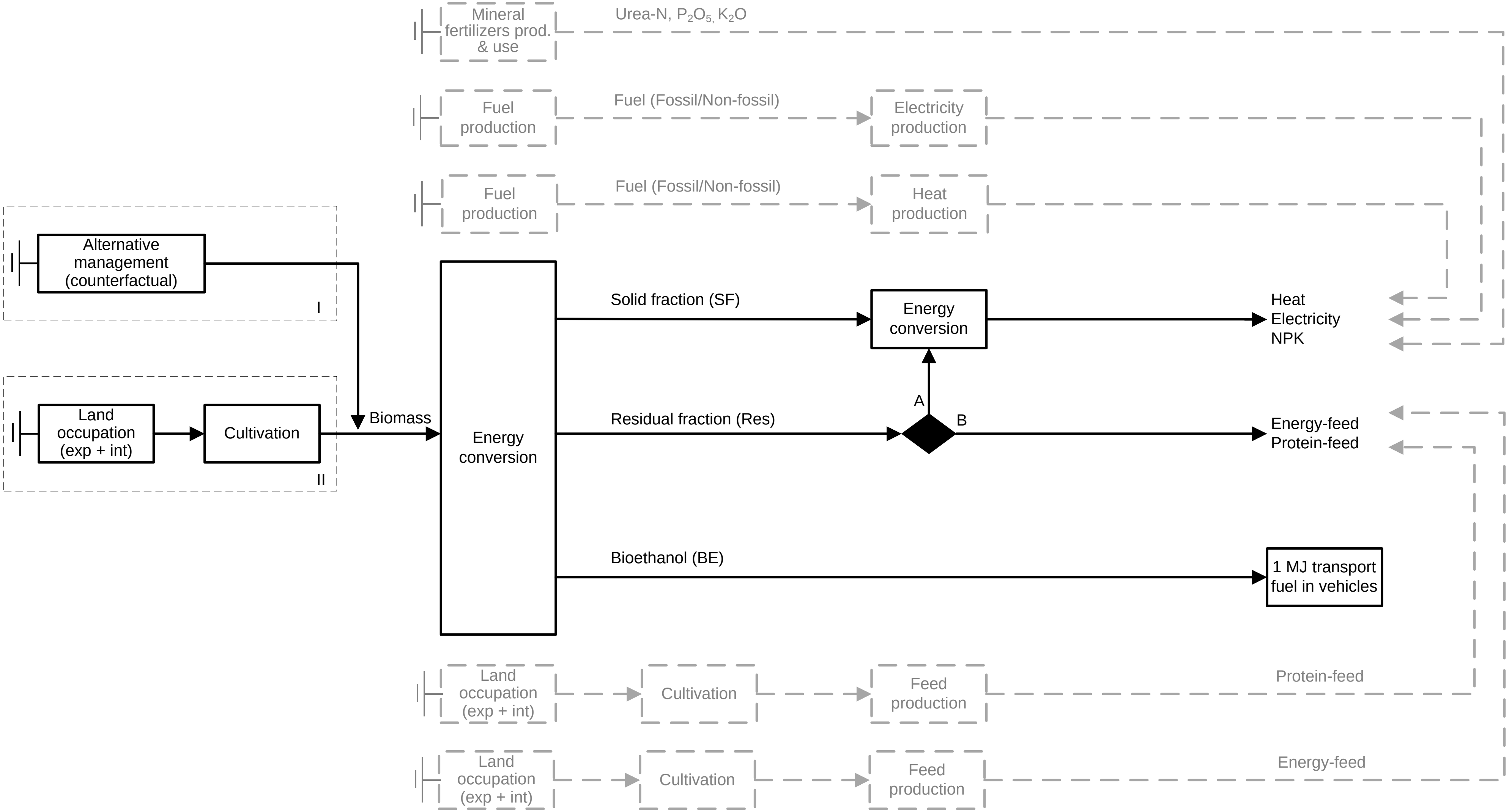
Figure 4. Breakdown of the GHG emissions for selected bioenergy pathways producing bioelectricity (scenarios namely Bel) under a fossil (a) and non-fossil (d) energy system, biomethane (scenarios namely BM) under a fossil (b) and non-fossil (e) energy system, and bioethanol (scenarios namely BE) under a fossil (c) and non-fossil (f) energy system. Induced effects include iLUC, crop cultivation, international shipping and substitution of mineral NPK fertilizers (i.e., all effects induced outside the energy system). The marginal fossil fuel (to produce the main energy service, i.e. 1 kWh electricity or 1 MJ transport fuel) is displayed as reference of comparison. CHP: combined heat and power; C6: C6 sugars; Comb: combustion; Res: residual fraction; SF: solid fraction; Syn: syngas.

Table 1. Alternative (counterfactual) management scenarios considered in this study and corresponding induced effects when changing the management of the biomasses (diversion to bioenergy). CHP: combined heat and power; LUC: land-use changes.

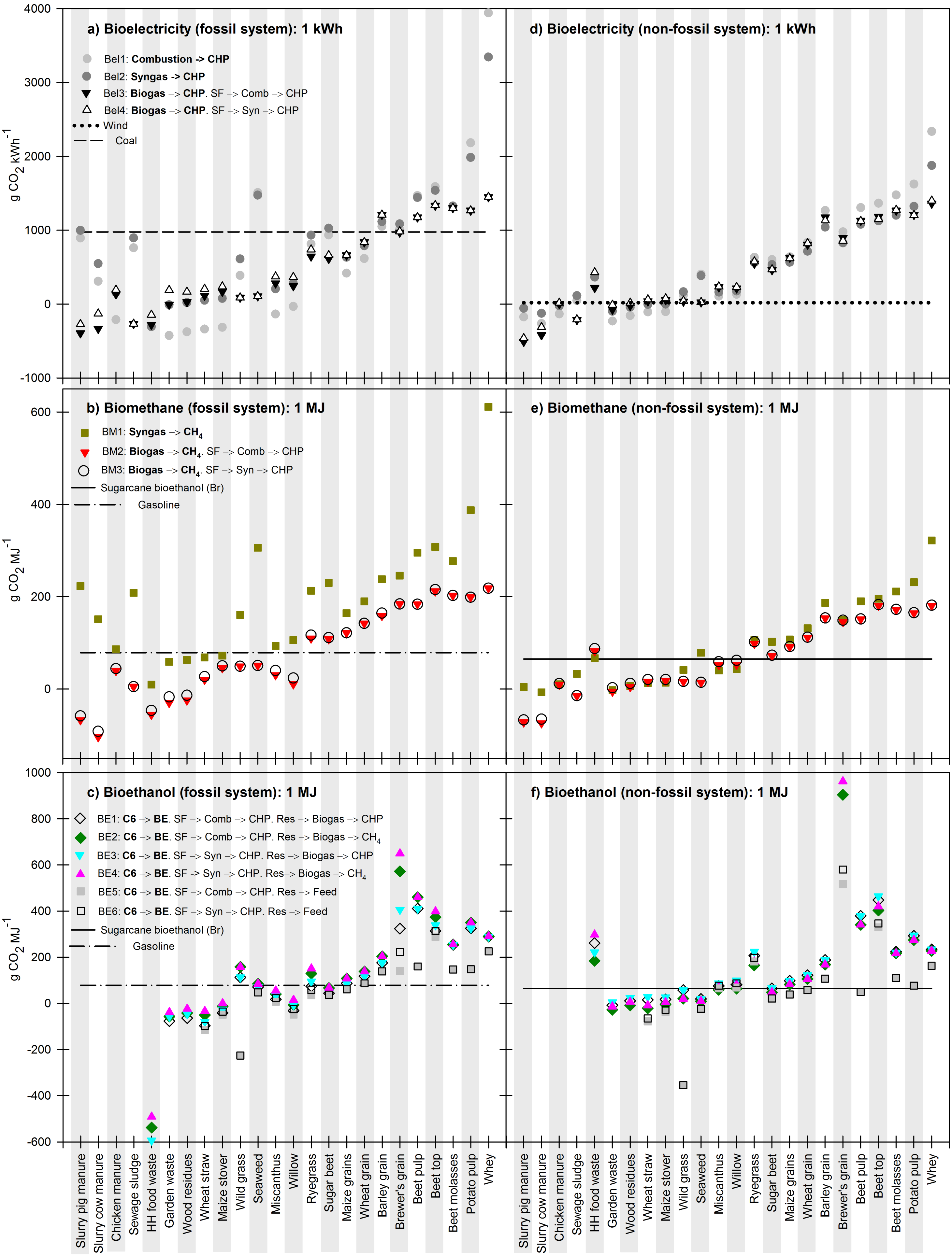
Biomass	Alternative (counterfactual) management	Induced effects (when changing the management)
Slurry pig manure	Conventional storage and use on-land without treatment	Avoided emissions of CH_4, N_2O, and NH_3 during storage
Slurry cow manure	Conventional storage and use on-land without treatment	Avoided emissions of CH_4, N_2O, and NH_3 during storage
Chicken manure	Conventional storage and use on-land without treatment	Avoided emissions of CH_4, N_2O, and NH_3 during storage
Sewage sludge	Dewatering and use on-land without treatment	Avoided emissions of CH_4, N_2O, and NH_3 during storage
Household food waste	Incineration CHP	Waste import, avoiding landfilling and generating CHP
Garden waste	Composting and use on-land of compost	Avoided composting and use on-land of compost
Wood residues	Left (and decayed) on-field	Avoided on-field decay (no return of C to the soil)
Wheat straw	Left (and decayed) on-field	Avoided on-field decay (no return of CNPK to the soil)
Maize stover	Left (and decayed) on-field	Avoided on-field decay (no return of CNPK to the soil)
Wild grass	Left (and decayed) on-field	Avoided on-field decay (no return of CNPK to the soil)
Seaweed[α]	-	-
Miscanthus	Alternative use of the land	Indirect LUC and cultivation of crop
Willow	Alternative use of the land	Indirect LUC and cultivation of crop
Ryegrass	Alternative use of the land	Indirect LUC and cultivation of crop
Sugar beet	Alternative use of the land	Indirect LUC and cultivation of crop
Maize grain	Alternative use of the land	Indirect LUC and cultivation of crop
Wheat grain	Alternative use of the land	Indirect LUC and cultivation of crop
Barley grain	Alternative use of the land	Indirect LUC and cultivation of crop
Brewer's grain	Use for feeding	Indirect LUC and cultivation of crop for feed provision
Beet pulp	Use for feeding	Indirect LUC and cultivation of crop for feed provision
Beet top	Use for feeding	Indirect LUC and cultivation of crop for feed provision
Beet molasses	Use for feeding	Indirect LUC and cultivation of crop for feed provision
Potato pulp	Use for feeding	Indirect LUC and cultivation of crop for feed provision
Whey	Use for feeding	Indirect LUC and cultivation of crop for feed provision

α Seaweed is farmed on sea. Here, we assume no effects due to farming practices.

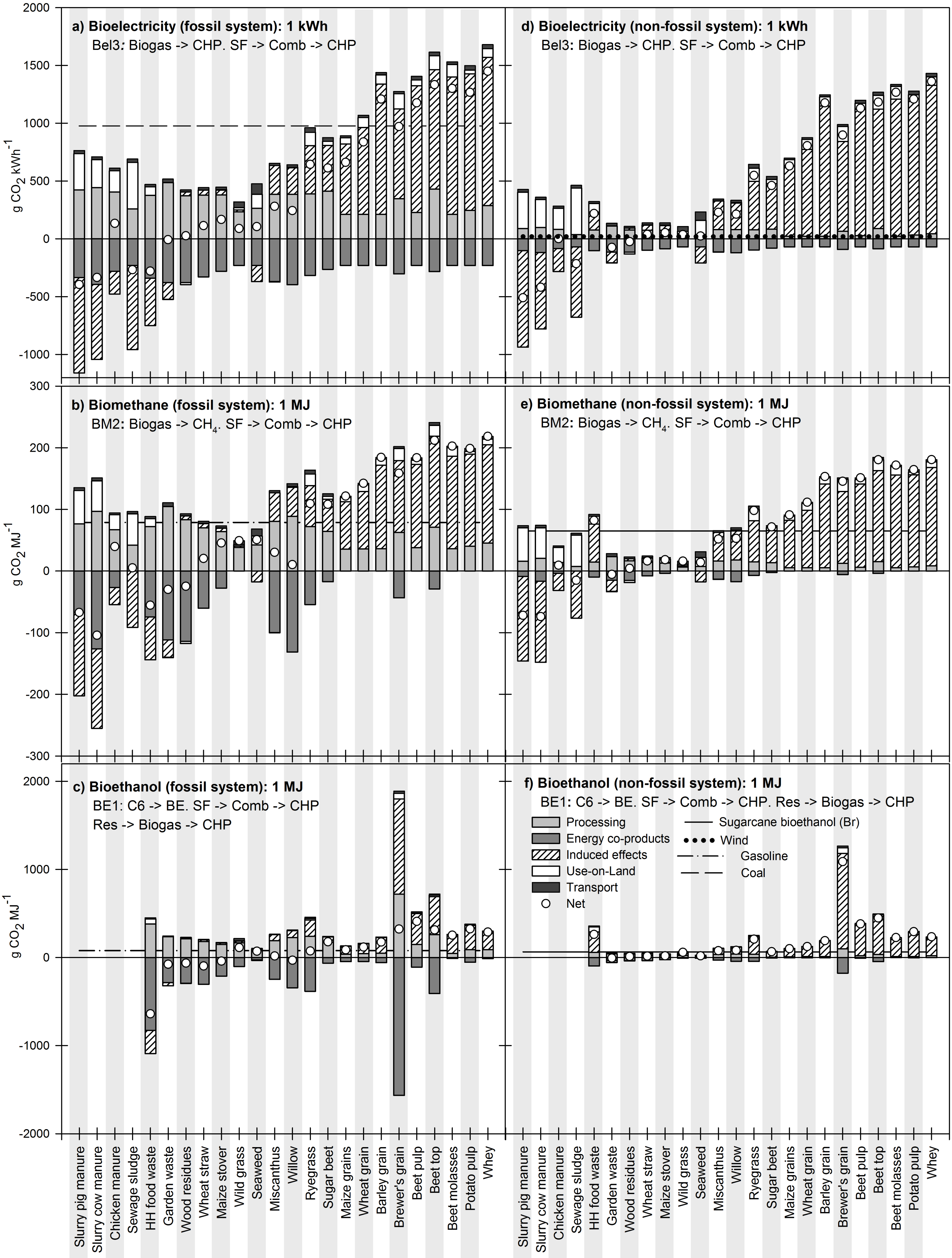

Slurry pig manure
Slurry cow manure
Chicken manure
Sewage sludge
Household food waste
Garden waste
Wood residue
Wheat straw
Maize stover
Wild grass
Seaweed
Miscanthus
Willow
Ryegrass
Sugar beet
Maize grain
Wheat grain
Barley grain
Brewer's grain
Beet pulp
Beet top
Beet molasses
Potato pulp
Whey
(I) 1 kWh bioelectricity (scenarios namely Bel)
(II) 1 MJ biomethane (scenarios namely BM)
(III) 1 MJ bioethanol (scenarios namely BE)
Bel1: Combustion → CHP
Bel2: Syngas → CHP
Bel3: Biogas → CHP. SF → Comb → CHP
Bel4: Biogas → CHP. SF → Syn → CHP
BM1: Syngas → CH_4
BM2: Biogas → CH_4. SF → Comb → CHP
BM3: Biogas → CH_4. SF → Syn → CHP
BE1: C6 → BE. SF → Comb → CHP. Res → Biogas → CHP
BE2: C6 → BE. SF → Comb → CHP. Res → Biogas → CH_4
BE3: C6 → BE. SF → Syn → CHP. Res → Biogas → CHP
BE4: C6 → BE. SF → Syn → CHP. Res → Biogas → CH_4
BE5: C6 → BE. SF → Comb → CHP. Res → Feed
BE6: C6 → BE. SF → Syn → CHP. Res → Feed



Mineral fertilizers prod. & use
Urea-N, P_2O_5, K_2O
Fuel production
Fuel (Fossil/Non-fossil)
Electricity production
Fuel production
Fuel (Fossil/Non-fossil)
Heat production
Alternative management (counterfactual)
I
Land occupation (exp + int)
Cultivation
II
Biomass
Energy conversion
Solid fraction (SF)
Energy conversion
Heat
Electricity
NPK
A
Residual fraction (Res)
B
Energy-feed
Protein-feed
Bioethanol (BE)
1 MJ transport fuel in vehicles
Land occupation (exp + int)
Cultivation
Feed production
Protein-feed
Land occupation (exp + int)
Cultivation
Feed production
Energy-feed



a) Bioelectricity (fossil system): 1 kWh
Bel1: Combustion -> CHP
Bel2: Syngas -> CHP
Bel3: Biogas –> CHP. SF –> Comb –> CHP
Bel4: Biogas –> CHP. SF –> Syn –> CHP
Wind
Coal
d) Bioelectricity (non-fossil system): 1 kWh
b) Biomethane (fossil system): 1 MJ
BM1: Syngas –> CH4
BM2: Biogas –> CH4. SF –> Comb –> CHP
BM3: Biogas –> CH4. SF –> Syn –> CHP
Sugarcane bioethanol (Br)
Gasoline
e) Biomethane (non-fossil system): 1 MJ
c) Bioethanol (fossil system): 1 MJ
BE1: C6 –> BE. SF –> Comb –> CHP. Res –> Biogas –> CHP
BE2: C6 –> BE. SF –> Comb –> CHP. Res –> Biogas –> CH4
BE3: C6 –> BE. SF –> Syn –> CHP. Res –> Biogas –> CHP
BE4: C6 –> BE. SF -> Syn –> CHP. Res–> Biogas –> CH4
BE5: C6 –> BE. SF –> Comb –> CHP. Res –> Feed
BE6: C6 –> BE. SF –> Syn –> CHP. Res –> Feed
Sugarcane bioethanol (Br)
Gasoline
f) Bioethanol (non-fossil system): 1 MJ
g CO2 kWh-1
g CO2 MJ-1
Slurry pig manure
Slurry cow manure
Chicken manure
Sewage sludge
HH food waste
Garden waste
Wood residues
Wheat straw
Maize stover
Wild grass
Seaweed
Miscanthus
Willow
Ryegrass
Sugar beet
Maize grains
Wheat grain
Barley grain
Brewer's grain
Beet pulp
Beet top
Beet molasses
Potato pulp
Whey


a) Bioelectricity (fossil system): 1 kWh
Bel3: Biogas -> CHP. SF -> Comb -> CHP
b) Biomethane (fossil system): 1 MJ
BM2: Biogas -> CH4. SF -> Comb -> CHP
c) Bioethanol (fossil system): 1 MJ
BE1: C6 -> BE. SF -> Comb -> CHP
Res -> Biogas -> CHP
d) Bioelectricity (non-fossil system): 1 kWh
Bel3: Biogas -> CHP. SF -> Comb -> CHP
e) Biomethane (non-fossil system): 1 MJ
BM2: Biogas -> CH4. SF -> Comb -> CHP
f) Bioethanol (non-fossil system): 1 MJ
BE1: C6 -> BE. SF -> Comb -> CHP. Res -> Biogas -> CHP
Processing
Energy co-products
Induced effects
Use-on-Land
Transport
Net
Sugarcane bioethanol (Br)
Wind
Gasoline
Coal
g CO2 kWh-1
g CO2 MJ-1
g CO2 MJ-1
Slurry pig manure
Slurry cow manure
Chicken manure
Sewage sludge
HH food waste
Garden waste
Wood residues
Wheat straw
Maize stover
Wild grass
Seaweed
Miscanthus
Willow
Ryegrass
Sugar beet
Maize grains
Wheat grain
Barley grain
Brewer's grain
Beet pulp
Beet top
Beet molasses
Potato pulp
Whey

Supporting information (SI) for:

GHG emission factors for bioelectricity, biomethane, and bioethanol quantified for 24 biomass substrates with consequential life-cycle assessment

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This SI document includes text, tables, and figures with details on the process data for the inventory analysis of the LCA. Additional information on results and sensitivity/uncertainty analyses are also provided.

Table of Contents

1. Life-cycle inventory

1.1 Biomass (bio)chemical and physical composition

The bio(chemical) composition of the twenty-four biomass substrates is detailed in Table S1. Data have been collected from multiple sources: chemical and biochemical composition of slurry pig and cow manure was taken from Hamelin et al. (2014). The composition of willow, *Miscanthus*, and ryegrass was taken from Tonini et al. (2012). The composition of chicken manure, barley, wheat, maize grains and maize stover was taken from Inra (2013). The composition of sewage sludge was based on Jimenez et al. (2013). The composition of household food waste was derived from Davidsson et al. (2007), garden waste from Boldrin and Christensen (2010) (for the chemical composition only, while biochemical composition was assumed to be equal to that of wood residues), wood residues from Energy Research Centre of the Netherlands (2011), seaweed from Alvarado-Morales et al. (2013), sugar beet from Moeller et al. (2000). The composition of wheat straw, wild grass, brewer's grain, beet pulp, beet top, beet molasses, potato pulp, and whey was taken from Tonini et al. (2015). Consistently, C content and LHV_{db} (lower heating value, dry basis) were quantified based on the biochemical composition following stoichiometry (same approach as in Tonini et al., 2015). For N content, the relationship proteins:6.25 was generally used, except for slurry manures for which we relied on the values from Hamelin et al. (2014). The parameter "digestibility" and "crude fibers", for all substrates, were taken from Inra, Cirad, FAO (2013). The theoretical methane potential was calculated conformingly with Symons and Buswell (1933) assuming methane potential of lignin equal to zero.

Table S1. Biochemical and chemical composition (selected parameters) of the twenty-four biomass substrates investigated. Digestibility; organic matter digestibility, ruminants; DM: dry matter; FU: feed units; HH: household; LHV_{db}: lower heating value, dry basis; nr: not relevant; SFU: Scandinavian Feed Units; VS: volatile solids; ww: wet weight.

Parameter	Unit	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Water	% ww	93.0	88.7	52.0	90.0	73.0	39.9	20.0	12.2	7.1	78.8	88.0	10.0	50.0	79.5	80.0	13.7	13.0	12.9	75.4	74.6	76.7	20.1	85.2	93.5
DM	% ww	7.0	11.3	48.0	10.0	27.0	60.1	80.0	87.8	92.9	21.2	12.0	90.0	50.0	20.5	20.0	86.3	87.0	87.1	24.6	25.4	23.3	79.9	14.8	6.5
VS	% DM	81.1	81.0	82.6	80.0	86.5	82.5	99.6	94.7	93.4	95.9	74.0	95.2	98.1	92.3	92.0	98.6	98.2	97.4	96.3	93.5	83.5	89.0	94.6	94.8
Ash	% DM	18.9	19.0	17.4	20.0	13.5	17.5	0.4	5.3	6.6	4.1	26.0	4.8	1.9	7.7	8.0	1.4	1.8	2.6	3.7	6.5	16.5	11.0	5.4	5.2
Sucrose	% DM	0.0	0.0	0.0	20.8	5.5	0.0	0.0	0.0	0.0	0.0	54.0	0.0	0.0	11.7	68.0	2.1	3.2	2.8	0.0	7.7	11.9	54.4	0.0	71.0
Starch	% DM	0.0	0.0	0.0	0.0	14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	73.4	69.1	59.7	1.4	0.0	3.6	2.0	36.8	0.0
Cellulose	% DM	13.6	20.8	18.0	0.0	0.0	36.8	44.5	34.7	41.2	29.1	6.0	47.6	41.2	19.0	8.0	2.4	2.5	5.3	17.7	23.9	11.2	2.2	21.0	0.0
Hemicellulose	% DM	13.6	20.8	17.9	0.0	0.0	17.1	20.6	22.4	14.9	24.2	0.0	18.5	14.9	20.6	8.0	9.2	10.3	15.3	29.5	25.8	16.2	0.0	9.0	0.0
Pectin	% DM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.0	8.2	0.0	21.9	0.0
Lignin	% DM	21.2	30.0	7.9	0.0	22.5	23.2	28.0	17.7	8.4	3.0	0.0	25.2	31.6	16.0	5.4	0.6	1.1	1.1	14.9	3.9	8.2	0.0	1.7	0.0
Proteins	% DM	27.0	16.8	24.2	46.5	14.0	0.0	0.0	3.5	3.7	5.2	12.0	2.8	3.8	18.7	7.4	9.4	12.6	11.8	23.1	8.6	16.9	12.7	6.0	10.8
Lipids	% DM	16.2	7.7	2.4	11.3	14.0	0.0	0.0	2.3	0.6	0.5	2.0	0.0	0.4	4.3	0.4	4.3	1.7	2.0	8.9	1.0	2.4	0.2	0.5	5.6
Acetic acid	% DM	8.5	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ethanol	% DM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C	% DM	47.6	46.6	39.6	40.2	47.8	41.7	50.4	46.4	42.7	42.4	32.7	48.1	50.7	46.5	41.2	45.9	45.0	44.7	50.1	42.9	39.9	38.0	43.0	42.4
N	% DM	7.86	5.60	3.87	7.44	2.24	0.39	0.12	0.56	0.59	0.84	1.92	0.44	0.60	2.99	1.2	1.50	2.02	1.89	3.69	1.34	2.70	2.04	1.05	1.73
P	% DM	1.62	0.91	1.98	0.28	0.45	0.06	0.00	0.05	0.07	0.40	0.40	0.49	0.07	0.40	0.11	0.30	0.36	0.39	0.52	0.13	0.18	0.03	0.03	1.24
K	% DM	4.1	5.2	1.6	0.4	1.1	0.5	0.0	1.0	1.4	0.3	0.0	0.7	0.3	0.3	0.33	0.4	0.5	0.6	0.0	0.4	4.8	3.6	0.2	2.9
Digestibility	% DM	nr	nr	73.1	nr	nr	nr	nr	44.0	55.2	78.0	80.3	nr	nr	78.0	90.0	88.5	88.2	85.0	61.4	83.0	82.0	89.3	90.0	94.0
crude fibers	% DM	nr	nr	18.5	nr	nr	nr	nr	45.3	42.4	24.9	8.3	nr	nr	24.9	5.4	2.5	2.6	5.2	16.7	20.8	12.0	0.1	24.0	0.0
SFU	FU kg^{-1}DM	nr	nr	nr	nr	nr	nr	nr	0.21	0.36	0.82	0.69	nr	nr	0.93	1.05	1.21	1.17	1.10	0.84	0.92	0.87	1.00	1.01	1.22
LHV_{db}	MJ kg^{-1}DM	18.8	18.4	15.3	16.7	19.7	15.7	19	17.5	15.6	15.3	12.3	18.1	19.4	18.1	15.3	16.6	16.2	16.1	19.9	15.6	15.2	14.1	15.1	16.2
LHV_{wb}	MJ kg^{-1}ww	-1	-0.1	6.1	-0.5	3.54	8.5	14.7	15.1	14.3	1.3	-0.7	16	8.5	1.8	1.1	14	13.8	13.7	3.1	2.1	1.7	10.7	0.2	-1.2
CH_4 potential$^{\alpha}$	NL kg^{-1}VS	453	335	416	546	417	298	298	355	385	410	444	307	287	387	400	446	431	432	426	411	408	428	416	460

α Theoretical methane potential calculated conformingly with Symons and Buswell (1933) assuming methane potential of lignin equal to zero.

1.2 Inventory data for technologies

Table S2. Technology data for anaerobic digestion (with relative biogas use), gasification (with relative syngas use), and combustion. CGE: cold gas efficiency (energy transfer biomass to syngas); CCE: carbon conversion efficiency (carbon transfer biomass to syngas); E: electricity; H: heat; LHV_{ar}: LHV as received, i.e. after drying/pelletization of the biomass; PT: pretreated; STP: standard T and P; $\eta_{E:}$ electricity recovery efficiency; $\eta_{H:}$ heat recovery efficiency; η_{UPG}: recovery efficiency of CH_4 during upgrading.

	Parameter	Unit	Value	Source/comment
Anaerobic digestion	E consum. comminution	kWh kg^{-1} DM	0.005	(Hamelinck et al., 2005) (not applied to whey/beet molasses/manures/sewage sludge)
	E consum. pretreatment	kWh kg^{-1} DM	11.4 (±2)	Only applied to straw/stover (extrusion) (Hjorth et al., 2011)
	H consum. pretreatment	MJ kg^{-1} DM	0.83 (±0.08)$^{\alpha}$	Only for wood residue (steam explosion) (Vivekanand et al., 2013; Uellendahl et al., 2008)
	Diesel for vehicles	L kg^{-1} ww	0.0009	Typical consumption
	CH_4 yield at plant	% CH_4 pot.	70 (±10)	Process efficiency(Angelidaki and Batstone, 2010)
	LHV CH_4 (STP)	MJ Nm^{-3}	38	At STP
	ρ CH_4	kg m^{-3}	0.714	At STP
	E consum. digestion	% $energy_{biogas}$	8 (±1.5)	5-11%, average of (Bacenetti et al., 2013; Boerjesson and Berglund, 2006; Hamelin et al., 2011)
	H consum digestion	MJ kg^{-1} ww	δ	Assuming DM content in the digester 10%
	CH_4 fugitive emission	%CH_4 produced	1	State-of-the-art plant with cover and insulation
Biogas use	η_E (gas engine)	% $energy_{biogas}$	45 (±2.5)	Average figure for 2015-2030 (Danish Energy Agency, 2012)
	η_H (gas engine)	% $energy_{biogas}$	45 (±2)	Average figure for 2015-2030 (Danish Energy Agency, 2012)
	η_{UPG} (upgrading to CH_4)	% $energy_{biogas}$	99.5	State-of-the art technology (Air Liquide Advanced Technologies, 2014)
	E consum. upgrading	kWh MJ^{-1}	0.016	Based on (Air Liquide Advanced Technologies, 2014)
Gasification	E consum. pelletization	kwh kg^{-1} DM	0.25 (±0.025)	Typical consumption (Jungbluth et al., 2007)
	H consum. pelletization	MJ kg^{-1} ww	3.3 (±0.33)	drying to 90% DM$^{\beta}$
	CGE (TC to syngas)	% $energy_{biomass}$	77 (±5)	Typical process efficiency (Arena et al., 2010)
	CCE (TC to syngas)	% C	96 (±2)	Typical process efficiency (Arena et al., 2010)
	TC to char	% DM	20 (±2)	Typical process efficiency (Arena et al., 2010)
	E consum.	kWh kg^{-1}_{ar}	0.075 (±0.008)	Typical consumption, based on Jungbluth et al. (2007)
	H consum./loss	% $energy_{biomass}$	21 (±1)	Process efficiency (Arena et al., 2010)
	LHV syngas	MJ Nm^{-3}	5.8 (±0.3)	Typical value, based on Arena et al. (2010)
Syngas use	η_E (gas engine)	% $energy_{biogas}$	45 (±2.5)	Average figure for 2015-2030 (Danish Energy Agency, 2012).
	η_H (gas engine)	% $energy_{biogas}$	45 (±2)	Average figure for 2015-2030 (Danish Energy Agency, 2012)
	η_{UPG} (upgrading to CH_4)	% $energy_{biogas}$	76.5	Typical efficiency, based on Jungbluth et al. (2007)

Combustion	E consum. pelletization	kWh kg^{-1} DM	0.25 (±0.025)	Typical consumption, based on (Jungbluth et al., 2007)
	H consum. pelletization	MJ kg^{-1} ww	3.3 (±0.33)	drying to 90% DM[β]
	η_E (CHP mode)	% LHV_{ar}	27 (±2)	Average figure for 2015-2030 (Danish Energy Agency, 2012)
	η_H (CHP mode)	% LHV_{ar}	76 (±2)	Average figure for 2015-2030 (Danish Energy Agency, 2012)

α Calculated as the thermal energy required to heat up the substrate (assuming the initial biomass is diluted with water or manure to reach 25% DM content) from 8 to 202°C (ΔT=194°C).

β Heat for drying varies depending upon substrate; it is quantified as the thermal energy required to dry the individual biomass from initial water content (Table S1) to the final water content of 10%, assuming the enthalpy of water at 2.44 MJ kg^{-1} water and a thermal efficiency of 75% (i.e. 2.44/0.75=3.3 MJ kg^{-1} water). For all substrates with DM<30% (e.g., pig and cow manure, grasses, beet pulp and molasses, whey, brewer's grain), a dewatering step with screw press is assumed in order to reach DM content of 30%. Thermal drying is then applied to reach DM=90%, required for pellets.

δ Varies depending upon DM content of the input-substrate. Heat for digestion is calculated as the thermal energy required to heat up the substrate (diluted down to 10% DM in the digester) from 8 to 38 °C (ΔT=30 °C), assuming latent heat of 3.3 MJ kg^{-1} DM for solids and 2.44 MJ kg^{-1} for water.

Table S3. Technology data for bioethanol production: main inventory parameters used in the study. C5, C6: sugar monomers with 5/6 carbon atoms; DH: dehydration; DR: drying; DT: distillation; DW: dewatering (mechanical separation); E: electricity; EtOH: ethanol; FE: fermentation; H: heat; Res: residual fraction (after eventual separation of the solid lignin fraction); na: not available; nr: not relevant in this study; PT: pretreatment; Sep: separation. Standard deviations are indicated between parentheses.

	Parameter	Unit	HH food waste Beet pulp Potato pulp$^{\alpha}$	Garden waste Wood residue Willow *Miscanthus*$^{\beta}$	Wheat straw Maize stover$^{\gamma}$	Res. grass Ryegrass Beet top$^{\delta}$	Seaweed$^{\varepsilon}$	Sugar beet$^{\zeta}$ Sugarcane	Maize grain Wheat grain Barley grain$^{\eta}$	Brewer's grain$^{\theta}$	Beet molasses$^{\iota}$	Whey$^{\kappa}$
Materials & Chemicals	NH_3	kg t^{-1} DM	17	17	3	17	-	-	-	17	-	-
	H_2SO_4	kg t^{-1} DM	190	31	6.3	190	-	8.7	8.7	190	9.4	1.9^{ζ}
	SO_4	kg t^{-1} DM	-	-	2.8	-	-	-	-	-	13	0.2^{ζ}
	$Ca(OH)_2$	kg t^{-1} DM	-	-	-	-	-	-	-	-	-	-
	$CaCl_2$	kg t^{-1} DM	-	-	0.3	-	-	-	-	-	-	-
	NaOH	kg t^{-1} DM	-	-	0.9	-	-	13	13	-	-	3^{ζ}
	Cellulase	kg t^{-1} DM	20	26	4.6	20	27	-	-	7.5	-	-
	Yeast	kg t^{-1} DM	16	16	15	16	16	16	16	16	na	na
	Sugar	kg t^{-1} DM	-	-	-	-	-	-	-	-	-	-
	CSL (N)	kg t^{-1} DM	20	-	na	-	-	-	-	-	-	-
	DAP (P)	kg t^{-1} DM	5	5	1.5	5	-	3.5	3.5	5	1.9	0.5^{ζ}
	Water	kg t^{-1} DM	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
Electricity & Heat	E (PT)	kWh t^{-1} DM	25 (±)	70 (±50)	79	71 (±45)	38 (±50)	78 (±7.8)*	28 (±2.8)	79	-	28
	H (PT)	MJ t^{-1} DM	460 (±120)	152 (±55)	560 (±45)	460 (±120)	460 (±120)	-	250 (±25)	460 (±120)	-	-
	E (FE)	kWh t^{-1} DM	67	67	67	67	67	-	20 (±2)	67	18	110
	H (FE)	MJ t^{-1} DM	-	-	-	-	-	-	-	-	-	-
	E (DT)	kWh t^{-1} DM	75	75	75	75	75		-	75	-	37
	H (DT)	MJ L^{-1}EtOH	18 (±11)	18 (±11)	7.3	18 (±11)	11 (±1.1)	2.8 (±)	2.4 (±0.24)	18 (±11)	1.2	7.3
	E (DH)	kWh t^{-1} ww	-	-	-	-	-	-	-	-	52	-
	H (DH)	MJ t^{-1} DM	-	-	-	-	-	-	2500 (±250)	-	2600	2100^{β}
	E (DW$^{\gamma}$)	kWh t^{-1} ww	24	24	24	24	24	24	nr	24	nr	nr
	H (DR)	MJ $kg^{-1}H_2O$	3.3	3.3	3.3	3.3	3.3	3.3	nr	3.3	nr	nr

Yield	$C6_{hydro}$	g C6 g^{-1} CE	0.91 (±)	0.87 (±0.12)	0.95 (±0.03)	0.79	0.87 (±0.1)	1	1	0.69	0.95 (±0.03)	0.95 (±0.03)
	$C5_{hydro}$	g C5 g^{-1} HC	0.56 (±)	0.6(±0.33)	0.75 (±0.1)	0.6	0.6 (±0.33)	0.97	0.97	0.48	0.75 (±0.1)	0.75 (±0.1)
	Yield	g EtOH g^{-1} C6	0.88 (±0.1)	0.9 (±0.09)	0.88 (±0.05)	0.92 (±0.09)	0.9 (±0.09)	0.81 (±0.08)	0.88 (± 0.1)	0.63 (±0.06)	0.88 (±0.05)	0.88 (±0.05)
Sep	N-protein	% to Res	33 (±3.3)	33 (±3.3)	33 (±3.3)	33 (±3.3)	nr	nr	nr	33 (±3.3)	nr	nr
	Lignin	% to Res	12 (±1.2)	7 (±0.7)	7 (±0.7)	3.9 (±0.4)	nr	nr	nr	7 (±0.7)	nr	nr

α Materials and Chemicals based on Zheng et al. (2014). Electricity and heat based on Bentsen et al. (2008) (except for Ht (PT) based on Zheng et al., 2014). Yields based on Zheng et al. (2014). Separation based on Bentsen et al. (2008).

β Materials and Chemicals based on Zhu and Pan (2010), Huang et al. (2009), Wooley et al. (1999). Electricity and heat based on Cardona Alzate and Sánchez Toro (2006), Humbird et al. (2011). Yields based on (Cardona Alzate and Sánchez Toro, (2006), Zhu and Pan (2010). Separation based on (Bentsen et al. (2008).

γ Materials and Chemicals based on Bentsen et al. (2008). Electricity and heat based on Hamelinck et al. (2005) (except for EL (DW) which is based on Grimwood, 2011 and Andriz Environment and Process, 2014)). Yields based on Hamelinck et al. (2005). Separation based on Bentsen et al. (2008).

δ Materials and Chemicals based on Shi et al. (2011), Sun and Cheng (2005). Electricity and heat based on Shi et al. (2011) and Sun and Cheng (2005). Yields based on Shi et al. (2011) and Sun and Cheng (2005). Separation based on Bentsen et al. (2008).

ε Materials and Chemicals based on Alvarado-Morales et al. (2013). Electricity and heat based on Alvarado-Morales et al. (2013). Yields based on Alvarado-Morales et al. (2013). No separation (no lignin fraction).

ζ Materials and Chemicals based on Ometto et al. (2009) (proxy with sugarcane bioethanol). Electricity and heat based on Ometto et al. (2009). Yields based on Ometto et al. (2009). For sugar beet no separation was assumed (no lignin fraction).

η Materials and Chemicals based on Jungbluth et al. (2007). Electricity and heat based on Jungbluth et al. (2007). Yields based on Jungbluth et al. (2007). No separation (no lignin fraction).

θ Materials and Chemicals based on White et al. (2008). Electricity and heat based on White et al. (2008). Yields based on White et al. (2008). Separation based on Bentsen et al. (2008).

ι Materials and Chemicals based on Jungbluth et al. (2007). Electricity and heat based on Jungbluth et al. (2007). Yields based on Tonini et al. (2015). No separation (no lignin fraction).

κ Materials and Chemicals based on Jungbluth et al. (2007) . Electricity and heat based on Jungbluth et al. (2007). Yields based on Jungbluth et al. (2007). No separation (no lignin fraction).

* Total electricity consumed in the biorefinery process (only the total is reported in Ometto et al., 2009).

1.3 Inventory data for (indirect) land use changes (iLUC)

Table S4. Final aggregated inventory for land use (1 ha of arable land demanded). After Tonini et al. (2015).

Expansion	**Emissions to air**		
	CO_2	2.2	t CO_2 $ha^{-1}{}_{dem}$ y^{-1}
	N_2O	0.22	kg N_2O $ha^{-1}{}_{dem}$ y^{-1}
	NO_x	1.8	kg NO $ha^{-1}{}_{dem}$ y^{-1}
Intensification: NPK fertilizer production	**Materials**		
	N-fertilizer	125	kg N $ha^{-1}{}_{dem}$ y^{-1}
	P-fertilizer	52	kg P_2O_5 $ha^{-1}{}_{dem}$ y^{-1}
	K-fertilizer	35	kg K_2O $ha^{-1}{}_{dem}$ y^{-1}
Intensification: N-emissions	**Emissions to air**		
	N_2O (dir + ind)*	3.4	kg N_2O $ha^{-1}{}_{dem}$ y^{-1}
	NH_3	3	kg NH_3 $ha^{-1}{}_{dem}$ y^{-1}
	NO_x	4.5	kg NO_2 $ha^{-1}{}_{dem}$ y^{-1}
	Emissions to water		
	NO_3-N	25	kg NO_3-N $ha^{-1}{}_{dem}$ y^{-1}

* Sum of direct and indirect N_2O.

1.4 Inventory data for energy crop production

Table S5. Inventory data for energy crop production, Denmark. After Hamelin et al. (2012)[1].

Crops	Plantation life time y	CAN (as N) kg ha^{-1} y^{-1}	DAP (as P_2O_5) kg ha^{-1} y^{-1}	KCl (as K_2O) kg ha^{-1} y^{-1}	Lime kg ha^{-1} y^{-1}	Pesticides (aggregated) kg ha^{-1} y^{-1}	cutting/ rhizome/ seed* kg ha^{-1} y^{-1}	Yield t ha^{-1} y^{-1}
Willow production	21	90	30	51	42	1.4	0.002	12.7 (±4)
Miscanthus (Spring) production	20	21	16	50	42	1.9	0.010	10 (±3.7)
Ryegrass production	2	310	83	290	42	0.65	21	13.6 (±4.5)
Beet production	1	84	99	180	170	6.4	1.7	13 (±0.95)
Maize production	1	61	52	114	170	0.80		4.7 (±0.38)
Wheat production	1	150	50	80	170	2.0		6.25 (±0.4)
Spring barley production	1	110	50	54	170	0.17		4.58 (±0.28)
Miscanthus (Winter) production	20	37	8.4	33	42	1.9	0.01	2.39 (±0.23)

[1] All data shown with a maximum of 2 significant digits. CAN: Calcium ammonium nitrate; DAP: Diammonium phosphate; KCl: Potassium chloride. Results are presented for a sandy soil, under "wet conditions" (964 mm rain per y).

* Expressed as ha^{-1} for willow and *Miscanthus*

1.5 GHG EFs of background processes

Table S6. List of GHG EFs for the background processes used in the assessment (capital goods excluded). In brackets are reported the GHG EF under the non-fossil energy system, when relevant.

Process	GHG EF	Source
Coal-electricity production & combustion	977 g CO_2-eq. kWh^{-1}	Taken from (Ecoinvent Centre, 2015)
Wind-electricity production & combustion	19 g CO_2-eq. kWh^{-1}	Taken from (Ecoinvent Centre, 2015)
Natural gas-heat production & combustion	64 g CO_2-eq. MJ^{-1}	Taken from (Ecoinvent Centre, 2015)
Gasoline in vehicles production & combustion	79 g CO_2-eq. MJ^{-1}	Taken from (Ecoinvent Centre, 2015)
SC bioethanol in vehicles production & combustion	65 g CO_2-eq. MJ^{-1}	See section 1.7 of this document for modelling details
Urea-N fertilizer production	2.6 g CO_2-eq. kg^{-1} N	Taken from (Ecoinvent Centre, 2015)
DAP fertilizer production	1.4 kg CO_2-eq. kg^{-1} P_2O_5	Taken from (Ecoinvent Centre, 2015)
K_2O fertilizer production	0.38 kg CO_2-eq. kg^{-1} K_2O	Taken from (Ecoinvent Centre, 2015)
Celluclast production	3.4 kg CO_2-eq. kg^{-1} ww	Taken from (Boldrin, Balzan and Astrup, 2013)
Lyposyme production	4.1 kg CO_2-eq. kg^{-1} ww	Taken from (Boldrin, Balzan and Astrup, 2013)
NH_3 production	2.7 kg CO_2-eq. kg^{-1} ww	Taken from (Ecoinvent Centre, 2015)
Methanol production & combustion	1.7 kg CO_2-eq. kg^{-1} ww	Taken from (Ecoinvent Centre, 2015)
NaOH production	0.34 kg CO_2-eq. kg^{-1} ww	Taken from (Ecoinvent Centre, 2015)
H_2SO_4 production	0.12 kg CO_2-eq. kg^{-1} ww	Taken from (Ecoinvent Centre, 2015)
H_3PO_4 production	1.3 kg CO_2-eq. kg^{-1} ww	Taken from (Ecoinvent Centre, 2015)
Seaweed production (DK)	0.29 kg CO_2-eq. kg^{-1} ww	Quantified based on the inventory provided in (Alvarado-Morales et al., 2013)
Miscanthus production (DK)	-0.17 kg CO_2-eq. kg^{-1} ww	Taken from (Hamelin et al., 2012). Inventory in Table S5
Willow production (DK)	0.35 kg CO_2-eq. kg^{-1} ww	Taken from (Hamelin et al., 2012). Inventory in Table S5
Ryegrass production (DK)	0.11 kg CO_2-eq. kg^{-1} ww	Taken from (Hamelin et al., 2012). Inventory in Table S5
Sugar beet production (DK)	0.056 kg CO_2-eq. kg^{-1} ww	Taken from (Hamelin et al., 2012). Inventory in Table S5
Maize production (DK)	0.11 kg CO_2-eq. kg^{-1} ww	Taken from (Hamelin et al., 2012). Inventory in Table S5
Wheat production (DK)	0.48 kg CO_2-eq. kg^{-1} ww	Taken from (Hamelin et al., 2012). Inventory in Table S5
Spring barley production (DK)	0.72 kg CO_2-eq. kg^{-1} ww	Taken from (Hamelin et al., 2012). Inventory in Table S5
Maize production (global)	0.4 kg CO_2-eq. kg^{-1} ww	Conformingly with (Tonini, Hamelin and Astrup, 2015) for determining marginal suppliers and using crop inventory from
Soybean production (global)	0.38 kg CO_2-eq. kg^{-1} ww	Conformingly with (Tonini, Hamelin and Astrup, 2015) for determining marginal suppliers and using crop inventory from
Palm fruit production (global)	0.1 kg CO_2-eq. kg^{-1} ww	Conformingly with (Tonini, Hamelin and Astrup, 2015) for determining marginal suppliers and using crop inventory from
Sugarcane production (Brazil)	0.05 kg CO_2-eq. kg^{-1} ww	Conformingly with (Tonini, Hamelin and Astrup, 2015) for determining marginal suppliers and using crop inventory from

Pig manure storage & UOL*	0.058 kg CO_2-eq. kg^{-1} ww	Storage: 0.065, UOL & transport: -0.07 kg CO_2-eq. kg^{-1} ww Following Hamelin et al. (2011, 2013)
Cow manure storage & UOL*	0.067 kg CO_2-eq. kg^{-1} ww	Storage: 0.083, UOL & transport: -0.016 kg CO_2-eq. kg^{-1} ww Following Hamelin et al. (2011, 2013)
Chicken manure storage & UOL*	0 kg CO_2-eq. kg^{-1} ww	Storage: 0.044, UOL & transport: -0.044 kg CO_2-eq. kg^{-1} ww Following Hamelin et al. (2011, 2013)
HH food waste (FW) No-landfill & incineration*	-0.14 kg CO_2-eq. kg^{-1} FW $(0.191)^{\alpha}$	Values are for approach B. See section 1.6 of this document for modelling details
Garden waste composting & UOL*	0.093 kg CO_2-eq. kg^{-1} ww (0.052)	Based on the inventory data for the composting tunnel (plant in Treviso, Italy) provided in (Boldrin et al., 2009)
Sewage sludge Dewatering & UOL*	0.047 kg CO_2-eq. kg^{-1} ww (0.031)	Sum of dewatering (23), UOL (47), transport (11), and mineral NPK fertilizer substitution (-34) following (Yoshida, 2014)
Straw/stover Left and decayed on-field*	0.088 kg CO_2-eq. kg^{-1} ww	Conformingly with (Tonini, Hamelin and Astrup, 2015)
Wood residues Left and decayed on-field*	0.045 kg CO_2-eq. kg^{-1} ww	Conformingly with (Wenzel et al., 2014; Schmidt and Brandao, 2013)
Wild grass Left and decayed on-field*	0.019 kg CO_2-eq. kg^{-1} ww	Conformingly with (Tonini, Hamelin and Astrup, 2015)
Transport lorry	75 g CO_2-eq. tkm^{-1}	Taken from (Ecoinvent Centre, 2015)
Transport oversea	8.5 g CO_2-eq. tkm^{-1}	Taken from (Ecoinvent Centre, 2015)

α When using approach A the GHG EF equals -0.248 (fossil energy system) and -0.04 (non-fossil energy system) kg CO_2-eq. kg^{-1} household food waste (diverted from incineration, wet basis).
*Counterfactual (alternative management) of the biomass, as assumed in this study.

1.6 GHG EF for imported MSW

According with Manfredi et al. (2009) the GHG of mixed municipal solid waste (MSW) landfilling in Europe, excluding open dumps, varies between 162 (conventional landfill with flaring) and -74 (state-of-the-art landfill with biogas recovery for energy use) kg CO_2-eq. t^{-1} ww. In this study, it is assumed that the imported mixed MSW would be otherwise landfilled in a state-of-the-art landfill with energy recovery. The LHV_{wb} of the mixed MSW was assumed equal to 9.2 GJ t^{-1} MSW (Tonini et al., 2013) with a fossil C content equal to 94 kg t^{-1} MSW (Astrup et al., 2009). The GHG emission factor for incineration of waste in Denmark was quantified conformingly with the approach of (Astrup et al., 2009) (Table 4 of the paper, for the case of coal-electricity: upstream 151 kg CO_2-eq t^{-1} ww, operation 371 kg CO_2-eq t^{-1} ww, electricity/heat recovery calculated on the basis of the LHV_{wb} of the MSW assuming efficiencies for electricity and heat of 27% and 76% as in Table S2). Transport was based on typical EU distances for transport of waste (2000 km on road and 500 km oversea).

Based on energy content, for each t of household food waste diverted from incineration (LHV_{wb}: 3.54 GJ t^{-1} ww, Table S1), 0.38 t of mixed MSW should be imported (i.e. 3.54/9.2) to guarantee the same thermal energy input to the incineration plant. The GHG emission factor for imported MSW can be then calculated according with Equation S1, and equals -365 kg CO_2-eq. t^{-1} $MSW_{imported}$ in the fossil energy system and 523 kg CO_2-eq. t^{-1} $MSW_{imported}$ in the non-fossil energy system.

Using approach A (incinerators react to diversion of household food waste), this GHG EF can then be referred to the "diverted" household food waste according with Equation S2, equaling -0.14 kg CO_2-eq. kg^{-1} household food waste (diverted from incineration, wet basis) in the fossil energy system and 0.2 kg CO_2-eq. kg^{-1} household food waste (diverted from incineration, wet basis) in the non-fossil energy system.

When using approach B (incinerators do not react to diversion of household food waste), the GHG EF of the household food waste "diverted" from incineration can be simply calculated according with Equation S3, equaling -0.248 kg CO_2-eq. kg^{-1} household food waste (diverted from incineration, wet basis) in the fossil energy system and -0.04 kg CO_2-eq. kg^{-1} household food waste (diverted from incineration, wet basis) in the non-fossil energy system.

$$
\begin{aligned}
&GHG\,EF_{MSW\,imported} = \\
&-landfilling_{EU} + Incineration_{DK} + Transport_{EU\rightarrow DK} = \\
&-landfilling_{EU} + (upstream + operation + electricity\,subst. - heat\,subst.)_{Incineration,DK} + (Road + Shipping)_{Transport,EU\rightarrow DK} = \\
&-(-74) + (158 + 371 - 674 - 448) + (150 + 4) = -365\,kg\,CO_2 - eq\,t^{-1} MSW_{imported}\ \ (fossil\,energy\,system) \\
&-(-74) + (72 + 371 - 13 - 136) + (150 + 4) = 523\,kg\,CO_2 - eq\,t^{-1} MSW_{imported}\ \ (non-\ fossil\,energy\,system)
\end{aligned}
$$

Equation S1

$$
\begin{aligned}
&GHG\,EF_{Household\ food\ waste}\ (approach\ B) = \frac{LHV_{wb,HFW}}{LHV_{wb,MSW\,imported}} \cdot GHG\,EF_{MSW\,imported} = \\
&\frac{3.54}{9.2} \cdot (-365) = -140\,kg\,CO_2 - eq\,t^{-1}\,ww_{HFW}\ \ (fossil\,energy\,system) \\
&\frac{3.54}{9.2} \cdot (523) = 200\,kg\,CO_2 - eq\,t^{-1}\,ww_{HFW}\ \ (non-\ fossil\,energy\,system)
\end{aligned}
$$

Equation S2

$$
\begin{aligned}
&GHG\,EF_{Household\ food\ waste}\ (approach\ A) = -Incineration_{HFW,DK} = \\
&-(upstream + operation - electricity\,subst. - heat\,subst.)_{Incineration,HFW,DK} \\
&-(158 + 26 - 259 - 173) = 248\,kg\,CO_2 - eq\,t^{-1}\,ww_{HFW}\ \ (fossil\,energy\,system) \\
&-(72 + 26 - 5 - 52) = -0.04\,kg\,CO_2 - eq\,t^{-1}\,ww_{HFW}\ \ (non-\ fossil\,energy\,system)
\end{aligned}
$$

Equation S3

1.7 GHG EF for sugarcane bioethanol for use in vehicles

The technology data used to quantify the GHG emissions for sugarcane bioethanol production (and combustion in vehicles) can be found in Table S2 (same as sugar beet). The GHG EF of marginal electricity provision in Brazil was quantified following the approach of Schmidt and Brandao (2013) (coal 7.5%, natural gas 35.3%, wood residues 5.2%, nuclear 5.8%, hydropower 40.5%, wind power 4.6%, photovoltaics 1.2%) and equaled 320 g CO_2-eq. kWh^{-1}. The marginal heat provision was assumed based on natural gas (GHG EF 64 g CO_2-eq. MJ^{-1}, see Table S5). Based on the biochemical model detailed in Tonini et al. (2015), using the data input detailed in Table S2, 1 t ww sugarcane, i.e. 320 kg DM (DM 32% of ww, ash 7%, sucrose 44%, cellulose 26%, hemicellulose 21%, lignin 4%, lipids 2%, proteins 4% of DM), produces: 69 kg bioethanol (1900 MJ), 66 kg CO_2, 150 kg DM solid fraction (also called bagasse, LHV_{db}: 17.7 MJ kg^{-1} DM) and 43 kg DM residual liquid fraction (also called vinasses). The difference between DM in and out is due to the water added (and related hydrolysis of sucrose). The partitioning of cellulose, hemicellulose, N, P, and K between liquid (vinasses) and solid (bagasse) was calculated after Christofoletti et al. (2013) and equaled 22%, 13%, 19%, 6%, and 89%, respectively. The bagasse was assumed combusted in boiler to provide process-heat to the refinery. Excess bagasse was assumed to be used for electricity production (assuming η_{el} 27%, as in Table S2) displacing marginal Brazilian electricity. Vinasses were assumed to be used on-land substituting for marginal mineral NPK fertilizers.

Table S7. Mass and energy balance for the production of 1 MJ bioethanol (BE) from sugarcane.

Parameter	Unit	per t ww sugarcane	per MJ bioethanol
Mass in	kg ww	1000	0.53
E in	kWh	70	0.037
H in	MJ	704	0.37
E out	kWh	197	0.1
H out	MJ	704	0.37
CH_4 out	MJ	0.00	0
BE_{out}	MJ	1900	1
$Feed_{out}$	SFU	0	0
N out	kg N	0.36	1.9e-4
P out	kg P	0.02	1.1e-5
K out	kg K	5.8	3e-3

Table S8. GHG EF for production and combustion in vehicles of sugarcane bioethanol. GHG emissions are provided both per tonne of ww sugarcane treated and per MJ of biofuel-energy combusted in the vehicles.

Process	kg CO_2 t^{-1} ww	g CO_2-eq. MJ^{-1}
Processing	102	54
Energy substitution	-109	-58
Use-on-land	3.3	1.7
Crop cultivation	50	26
iLUC	62	33
Fertilizer substitution	-3	-1.6
Transport	18	9.4
Total	123 (±11)	65 (±5)

1.8 Substitution of mineral fertilizers

The digestate from anaerobic digestion of the biomass substrates was assumed to be used on-land for substitution of inorganic NPK fertilizers. The calculation of the amount of mineral fertilizers substituted from using the digestates as organic fertilizers was based on the Danish law (Danish Ministry of Food, Agriculture and Fisheries, 2008). This follows the European legislation on organic fertilizer application which imposes an upper cap on the amount of N that can be brought on-field (The Council of the European Communities, 1991). Based on Danish Ministry of Food, Agriculture and Fisheries (2008), it was assumed that the N in the digestate substituted mineral N-fertilizer with an efficiency of 75% (this, under the assumption that the biomass substrates are co-digested with manure in the ratio manure: co-substrate = 3:1 on a wet basis).

On the other hand, the P and K may be applied in excess, as they are not limited as in the case of N. In situations where these are applied in excess, the amount of mineral P and K fertilizers that are avoided should not include the amount of P and K contributing to the excess (Hamelin et al., 2011), the rationale being that without the digestate, farmers would only apply minerals P and K up to the crop requirements, in order to save on costs. The proportion of P and K from the applied digestate that are really avoided was therefore calculated as the ratio between the average annual needs in P and K from the crop rotation considered (23 kg P ha^{1} y^{1} and 61 kg K ha^{1} y^{1}, see Table S8), and the content of P and K in the digestate applied.

Table S9. P and K requirements of the 6year crop rotation where the digestate is applied.

Year	Crop	P (kg ha^{1})$^{\alpha}$	K (kg ha^{1})$^{\alpha}$
1	Winter barley	21	54
2	Winter rape	30	89
3	Winter maize	22	66
4	Winter wheat	22	66
5	Spring barley	22	45
6	Spring barley	22	45
Annual average		23	61

α Data for P and K requirements are from Danish Ministry of Food, Agriculture and Fisheries (2006).

1.9 Transport

The following distances were considered for transportation:

- Biomass from point of generation to processing plant: 30 km (road)
- Liquid/solid fuel produced at processing plant to service/power station: 200 km (road)
- Residual digestate to use-on-land: 30 km (road)
- Imported energy-feed (maize): 11400 km (oversea)
- Imported protein-feed (soymeal): 11800 km (oversea)
- Imported MSW waste: 2000 km (road) and 500 km (oversea)

The datasets used for road transport and shipping are detailed in Table S6.

2. Mass and energy balances of the scenarios

Mass and energy balances for the scenarios investigated are detailed in Table S10-S21. The functional unit (service provided) is highlighted in grey. The units are as follows:

- $Mass_{in}$: mass input (kg ww)
- E_{in}: electricity input (kWh)
- H_{in}: heat input (MJ)
- E_{out}: electricity output (kWh)
- H_{out}: heat output (MJ)
- CH_{4out}: methane output (MJ)
- BE_{out}: ethanol output (MJ)
- $Feed_{out}$: feed output (Scandinavian Feed Units, SFU)
- N_{out}: nitrogen output, in the digestate applied on-land (g N)
- P_{out}: phosphorus output, in the digestate applied on-land (g P)
- K_{out}: potassium output, in the digestate applied on-land (g K)

Notice that the NPK content of the digestate does not reflect the actual substitution of NPK mineral fertilizers, as this depends upon the substitution efficiency. This equals 75% for N (see section 1.8 of this document). For P and K, instead, the substitution efficiency was calculated according with the approach of Tonini et al. (2015), Tonini et al. (2012), Hamelin et al. (2011) and ranged between 70% and 100%.

2.1 Mass/energy balance for production of bioelectricity (1 kWh)

Table S10. Production of 1 kWh bioelectricity. Mass and energy balances. Scenario Bel1: Combustion → CHP; nr: not relevant.

Parameter	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Mass$_{in}$	9.7	6.3	1.8	8.2	nr	1.4	0.9	0.9	0.9	4.2	9.6	0.8	1.4	3.7	4.6	0.9	1.0	1.0	2.8	3.5	3.9	1.2	6.1	13.1
E$_{in}$	0.19	0.20	0.25	0.23	nr	0.24	0.20	0.21	0.24	0.24	0.32	0.21	0.19	0.21	0.26	0.23	0.23	0.23	0.19	0.25	0.25	0.28	0.25	0.24
H$_{in}$	29.5	18.2	2.8	24.1	nr	1.6	0.3	0.1	0.0	10.6	27.4	0.0	2.1	9.4	11.8	0.1	0.1	0.1	6.6	8.2	9.4	0.5	17.0	40.2
E$_{out}$	1	1	1	1	nr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
H$_{out}$	10.1	10.1	10.1	10.1	nr	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
CH$_{4out}$	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BE$_{out}$	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feed$_{out}$	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N$_{out}$	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P$_{out}$	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K$_{out}$	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table S11. Production of 1 kWh bioelectricity. Mass and energy balances. Scenario Bel2: Syngas → CHP.

Mass$_{in}$	7.5	4.8	1.4	6.3	2.0	1.1	0.7	0.7	0.7	3.2	7.3	0.6	1.1	2.8	3.5	0.7	0.7	0.7	2.1	2.7	3.0	0.9	4.7	10.1
E$_{in}$	0.19	0.20	0.25	0.23	0.19	0.24	0.20	0.21	0.24	0.24	0.31	0.21	0.19	0.21	0.25	0.23	0.23	0.23	0.19	0.24	0.25	0.27	0.25	0.24
H$_{in}$	22.8	14.0	2.2	18.4	0.0	1.2	0.3	0.1	0.0	8.0	20.8	0.0	1.6	7.2	9.0	0.1	0.1	0.1	5.1	6.3	7.3	0.4	12.8	31.0
E$_{out}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
H$_{out}$	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
CH$_{4out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BE$_{out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feed$_{out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N$_{out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P$_{out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K$_{out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table S12. Production of 1 kWh bioelectricity. Mass and energy balances. Scenario Bel3: Biogas → CHP, SF → Comb → CHP.

Parameter	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
$Mass_{in}$	8.8	5.9	1.6	6.9	2.3	1.3	0.8	0.8	0.8	3.6	7.6	0.8	1.3	3.3	3.8	0.8	0.8	0.8	2.5	3.1	3.3	1.0	5.2	10.5
E_{in}	0.10	0.11	0.09	0.08	0.10	0.11	0.10	0.10	0.09	0.08	0.08	0.10	0.11	0.10	0.09	0.08	0.08	0.08	0.09	0.08	0.09	0.08	0.08	0.08
H_{in}	3.6	4.0	3.1	0.8	2.9	4.6	2.9	2.8	2.8	0.4	0.9	3.1	3.1	3.0	3.2	0.1	0.1	0.1	2.3	0.3	3.5	0.1	0.6	1.3
E_{out}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
H_{out}	5.2	6.2	4.4	3.6	5.3	5.9	5.9	5.1	4.4	3.6	3.6	5.8	6.2	4.9	4.1	3.6	3.6	3.6	4.7	3.6	4.4	3.6	3.6	3.6
CH_{4out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BE_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$Feed_{out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{out}	36.1	28.1	22.4	46.2	10.5	2.3	0.6	3.0	3.3	5.7	15.8	2.4	2.9	15.2	6.8	9.3	12.6	11.9	17.0	9.5	15.6	14.7	7.2	10.7
P_{out}	8.0	4.9	12.2	1.9	2.2	0.4	0.0	0.3	0.4	3.1	3.6	2.8	0.4	2.2	0.7	2.1	2.5	2.7	2.5	1.0	1.1	0.2	0.3	8.5
K_{out}	22.2	30.8	10.9	2.7	5.8	3.2	0.0	6.1	8.9	2.5	0.0	4.4	1.7	2.0	2.2	2.7	3.2	4.0	0.1	3.5	32.7	28.8	1.7	19.8

Table S13. Production of 1 kWh bioelectricity. Mass and energy balances. Scenario Bel4: Biogas → CHP, SF → Syngas → CHP.

$Mass_{in}$	8.2	5.3	1.6	6.9	2.1	1.2	0.7	0.7	0.8	3.6	7.6	0.7	1.2	3.1	3.7	0.8	0.8	0.8	2.3	3.1	3.2	1.0	5.2	10.5
E_{in}	0.10	0.11	0.09	0.08	0.10	0.11	0.11	0.10	0.09	0.08	0.08	0.11	0.11	0.10	0.09	0.08	0.08	0.08	0.09	0.08	0.09	0.08	0.08	0.08
H_{in}	3.3	3.6	3.0	0.8	2.7	4.3	2.6	2.7	2.7	0.4	0.9	2.8	2.8	2.8	3.2	0.1	0.1	0.1	2.2	0.3	3.4	0.1	0.6	1.3
E_{out}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
H_{out}	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
CH_{4out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BE_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$Feed_{out}$	8.2	5.3	1.6	6.9	2.1	1.2	0.7	0.7	0.8	3.6	7.6	0.7	1.2	3.1	3.7	0.8	0.8	0.8	2.3	3.1	3.2	1.0	5.2	10.5
N_{out}	36.1	28.1	22.4	46.2	10.5	2.3	0.6	3.0	3.3	5.7	15.8	2.4	2.9	15.2	6.8	9.3	12.6	11.9	17.0	9.5	15.6	14.7	7.2	10.7
P_{out}	8.0	4.9	12.2	1.9	2.2	0.4	0.0	0.3	0.4	3.1	3.6	2.8	0.4	2.2	0.7	2.1	2.5	2.7	2.5	1.0	1.1	0.2	0.3	8.5
K_{out}	22.2	30.8	10.9	2.7	5.8	3.2	0.0	6.1	8.9	2.5	0.0	4.4	1.7	2.0	2.2	2.7	3.2	4.0	0.1	3.5	32.7	28.8	1.7	19.8

2.2 Mass/energy balance for production of biomethane (1 MJ)

Table S14. Production of 1 MJ biomethane for use in vehicles. Mass and energy balances. Scenario BM1: Syngas → CH_4.

Parameter	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
$Mass_{in}$	1.22	0.80	0.23	1.04	0.32	0.18	0.11	0.11	0.12	0.52	1.21	0.10	0.18	0.46	0.58	0.12	0.12	0.12	0.35	0.42	0.48	0.16	0.76	1.69
E_{in}	0.04	0.05	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.07	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.05	0.05	0.06	0.05	0.05
H_{in}	3.73	2.32	0.36	3.06	0.75	0.19	0.04	0.01	0.00	1.31	3.46	0.00	0.26	1.16	1.48	0.02	0.01	0.01	0.84	0.99	1.18	0.06	2.11	5.19
E_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CH_{4out}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
BE_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$Feed_{out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table S15. Production of 1 MJ biomethane for use in vehicles. Mass and energy balances. Scenario BM2: Biogas → CH_4, SF → Comb → CHP.

$Mass_{in}$	1.44	1.19	0.23	0.87	0.39	0.26	0.16	0.12	0.11	0.46	0.95	0.14	0.27	0.52	0.50	0.10	0.10	0.10	0.37	0.38	0.48	0.12	0.65	1.31
E_{in}	3E-2	4E-2	3E-2	3E-2	0.035	4E-2	4E-2	3E-2	3E-2	3E-2	3E-2	4E-2	4E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2
H_{in}	-0.55	-0.78	-0.44	-0.10	-0.47	-0.92	-0.58	-0.45	-0.39	-0.05	-0.11	-0.56	-0.63	-0.49	-0.42	-0.01	-0.01	-0.01	-0.36	-0.04	-0.51	-0.01	-0.08	-0.16
E_{out}	0.04	0.08	0.02	0.00	0.05	0.07	0.07	0.04	0.02	0.00	0.00	0.06	0.08	0.03	0.01	0.00	0.00	0.00	0.03	0.00	0.02	0.00	0.00	0.00
H_{out}	0.42	0.79	0.17	0.00	0.46	0.70	0.71	0.37	0.17	0.00	0.00	0.62	0.81	0.34	0.11	0.00	0.00	0.00	0.27	0.00	0.18	0.00	0.00	0.00
CH_{4out}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
BE_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$Feed_{out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{out}	5.91	5.67	3.21	5.83	1.78	0.45	0.11	0.45	0.46	0.73	1.97	0.42	0.61	2.39	0.89	1.17	1.58	1.48	2.51	1.16	2.27	1.76	0.91	1.33
P_{out}	1.31	0.98	1.75	0.24	0.38	0.08	0.00	0.04	0.06	0.39	0.46	0.50	0.08	0.34	0.09	0.26	0.31	0.34	0.38	0.13	0.16	0.03	0.03	1.06
K_{out}	3.63	6.21	1.57	0.34	0.98	0.65	0.00	0.92	1.23	0.32	0.00	0.77	0.36	0.31	0.29	0.34	0.40	0.50	0.02	0.42	4.76	3.46	0.21	2.47

Table S16. Production of 1 MJ biomethane for use in vehicles. Mass and energy balances. Scenario BM3: Biogas → CH_4, SF → Syngas → CHP.

Parameter	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
$Mass_{in}$	1.44	1.19	0.23	0.87	0.39	0.26	0.16	0.12	0.11	0.46	0.95	0.14	0.27	0.52	0.50	0.10	0.10	0.10	0.37	0.38	0.48	0.12	0.65	1.31
E_{in}	3E-2	4E-2	3E-2	3E-2	0.035	4E-2	4E-2	3E-2	3E-2	3E-2	3E-2	4E-2	4E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2	3E-2
H_{in}	-0.55	-0.78	-0.44	-0.10	-0.47	-0.92	-0.58	-0.45	-0.39	-0.05	-0.11	-0.56	-0.63	-0.49	-0.42	-0.01	-0.01	-0.01	-0.36	-0.04	-0.51	-0.01	-0.08	-0.16
E_{out}	0.05	0.10	0.02	0.00	0.06	0.09	0.09	0.05	0.02	0.00	0.00	0.08	0.10	0.04	0.01	0.00	0.00	0.00	0.03	0.00	0.02	0.00	0.00	0.00
H_{out}	0.15	0.32	0.04	-0.04	0.17	0.26	0.29	0.14	0.04	-0.03	-0.03	0.24	0.32	0.11	0.02	-0.04	-0.04	-0.03	0.08	-0.03	0.06	-0.05	-0.04	-0.04
CH_{4out}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
BE_{out}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$Feed_{out}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{out}	5.91	5.67	3.21	5.83	1.78	0.45	0.11	0.45	0.46	0.73	1.97	0.42	0.61	2.39	0.89	1.17	1.58	1.48	2.51	1.16	2.27	1.76	0.91	1.33
P_{out}	1.31	0.98	1.75	0.24	0.38	0.08	0.00	0.04	0.06	0.39	0.46	0.50	0.08	0.34	0.09	0.26	0.31	0.34	0.38	0.13	0.16	0.03	0.03	1.06
K_{out}	3.63	6.21	1.57	0.34	0.98	0.65	0.00	0.92	1.23	0.32	0.00	0.77	0.36	0.31	0.29	0.34	0.40	0.50	0.02	0.42	4.76	3.46	0.21	2.47

2.3 Mass/energy balance for production of bioethanol (1 MJ)

Table S17. Production of 1 MJ bioethanol. Mass and energy balances. Scenario BE1: C6 → BE, SF → Comb → CHP, Res → Biogas → CHP.

Parameter	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
$Mass_{in}$	nr	nr	nr	nr	1.46	0.37	0.23	0.25	0.20	1.40	1.03	0.20	0.41	1.20	0.54	0.11	0.11	0.12	3.09	0.94	1.28	0.16	1.15	1.60
E_{in}	nr	nr	nr	nr	0.13	0.07	0.06	0.07	0.06	0.05	0.02	0.06	0.07	0.08	0.02	0.01	0.01	0.01	0.29	0.05	0.10	3E-3	0.03	0.02
H_{in}	nr	nr	nr	nr	2.9	2.1	1.9	1.2	1.1	1.0	0.5	1.7	2.0	1.8	0.2	0.4	0.4	0.4	4.7	0.9	1.6	0.4	0.4	1.1
E_{out}	nr	nr	nr	nr	0.56	0.19	0.19	0.21	0.14	0.08	0.02	0.16	0.22	0.26	0.05	0.04	0.04	0.05	1.07	0.09	0.28	0.01	0.04	0.01
H_{out}	nr	nr	nr	nr	4.5	1.6	1.6	1.6	1.1	0.30	0.08	1.4	2.0	2.0	0.23	0.14	0.13	0.17	8.09	0.32	2.1	0.03	0.16	0.04
CH_{4out}	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BE_{out}	nr	nr	nr	nr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$Feed_{out}$	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{out}	nr	nr	nr	nr	6.75	0.00	0.00	0.37	0.33	0.74	0.70	0.23	0.37	2.18	0.38	0.42	0.57	0.59	8.32	0.98	2.40	2.35	0.48	1.63
P_{out}	nr	nr	nr	nr	1.41	0.11	0.00	0.09	0.10	0.95	0.40	0.71	0.12	0.78	0.10	0.23	0.28	0.33	3.12	0.25	0.41	0.04	0.05	1.30
K_{out}	nr	nr	nr	nr	3.66	0.91	0.00	1.91	2.23	0.87	0.00	1.10	0.54	0.72	0.32	0.33	0.39	0.53	0.17	0.94	12.7	4.64	0.33	3.01

Table S18. Production of 1 MJ bioethanol. Mass and energy balances. Scenario BE2: C6 → BE, SF → Comb → CHP, Res → biogas → CH_4.

$Mass_{in}$	nr	nr	nr	nr	1.46	0.37	0.23	0.25	0.20	1.40	1.03	0.20	0.41	1.20	0.54	0.11	0.11	0.12	3.09	0.94	1.28	0.16	1.15	1.60
E_{in}	nr	nr	nr	nr	0.13	0.07	0.06	0.07	0.06	0.04	0.02	0.05	0.07	0.07	0.02	0.01	0.01	0.01	0.25	0.04	0.09	2E-3	0.03	0.02
H_{in}	nr	nr	nr	nr	2.9	2.1	1.9	1.2	1.1	1.0	0.5	1.7	2.0	1.8	0.2	0.4	0.4	0.4	4.7	0.9	1.6	0.4	0.4	1.1
E_{out}	nr	nr	nr	nr	0.54	0.14	0.15	0.12	0.09	0	0	0.12	0.18	0.16	0.01	0	0	0	0.65	0	0.17	0	0	0
H_{out}	nr	nr	nr	nr	3.9	1.5	1.5	1.3	0.9	0	0	1.2	1.8	1.7	0.1	0	0	0	6.6	0	1.8	0	0	0
CH_{4out}	nr	nr	nr	nr	1.45	0.34	0.35	0.67	0.40	0.67	0.18	0.32	0.33	0.79	0.33	0.30	0.29	0.39	3.41	0.72	0.82	0.07	0.35	0.08
BE_{out}	nr	nr	nr	nr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$Feed_{out}$	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{out}	nr	nr	nr	nr	6.75	0.00	0.00	0.37	0.33	0.74	0.70	0.23	0.37	2.18	0.38	0.42	0.57	0.59	8.32	0.98	2.40	2.35	0.48	1.63
P_{out}	nr	nr	nr	nr	1.41	0.11	0.00	0.09	0.10	0.95	0.40	0.71	0.12	0.78	0.10	0.23	0.28	0.33	3.12	0.25	0.41	0.04	0.05	1.30
K_{out}	nr	nr	nr	nr	3.66	0.91	0.00	1.91	2.23	0.87	0.00	1.10	0.54	0.72	0.32	0.33	0.39	0.53	0.17	0.94	12.7	4.64	0.33	3.01

Table S19. Production of 1 MJ bioethanol. Mass and energy balances. Scenario BE3: C6 → BE, SF → Syngas → CHP, Res → Biogas → CHP.

Parameter	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
$Mass_{in}$	nr	nr	nr	nr	1.46	0.37	0.23	0.25	0.20	1.40	1.03	0.20	0.41	1.20	0.54	0.11	0.11	0.12	3.09	0.94	1.28	0.16	1.15	1.60
E_{in}	nr	nr	nr	nr	0.15	0.08	0.07	0.08	0.07	0.05	0.02	0.06	0.08	0.09	0.02	0.01	0.01	0.01	0.33	0.05	0.11	3E-3	0.03	0.02
H_{in}	nr	nr	nr	nr	2.9	2.1	1.9	1.2	1.1	1.0	0.5	1.7	2.0	1.8	0.2	0.4	0.4	0.4	4.7	0.9	1.6	0.4	0.4	1.1
E_{out}	nr	nr	nr	nr	0.67	0.23	0.23	0.24	0.17	0.08	0.02	0.20	0.27	0.31	0.05	0.04	0.04	0.05	1.26	0.09	0.33	0.01	0.04	0.01
H_{out}	nr	nr	nr	nr	2.5	0.9	0.9	0.9	0.6	0.3	0.1	0.7	1.0	1.2	0.2	0.1	0.1	0.2	4.7	0.3	1.2	3E-2	0.2	4E-2
CH_{4out}	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BE_{out}	nr	nr	nr	nr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$Feed_{out}$	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{out}	nr	nr	nr	nr	6.75	0.00	0.00	0.37	0.33	0.74	0.70	0.23	0.37	2.18	0.38	0.42	0.57	0.59	8.32	0.98	2.40	2.35	0.48	1.63
P_{out}	nr	nr	nr	nr	1.41	0.11	0.00	0.09	0.10	0.95	0.40	0.71	0.12	0.78	0.10	0.23	0.28	0.33	3.12	0.25	0.41	0.04	0.05	1.30
K_{out}	nr	nr	nr	nr	3.66	0.91	0.00	1.91	2.23	0.87	0.00	1.10	0.54	0.72	0.32	0.33	0.39	0.53	0.17	0.94	12.7	4.64	0.33	3.01

Table S20. Production of 1 MJ bioethanol. Mass and energy balances. Scenario BE4: C6 → BE, SF → Syngas → CHP, Res → Biogas → CH_4.

$Mass_{in}$	nr	nr	nr	nr	1.46	0.37	0.23	0.25	0.20	1.40	1.03	0.20	0.41	1.20	0.54	0.11	0.11	0.12	3.09	0.94	1.28	0.16	1.15	1.60
E_{in}	nr	nr	nr	nr	0.13	0.07	0.07	0.07	0.06	0.04	0.02	0.06	0.08	0.08	0.02	0.01	0.01	0.01	0.29	0.04	0.10	0.00	0.03	0.02
H_{in}	nr	nr	nr	nr	2.9	2.1	1.9	1.2	1.1	1.0	0.5	1.7	2.0	1.8	0.2	0.4	0.4	0.4	4.7	0.9	1.6	0.4	0.4	1.1
E_{out}	nr	nr	nr	nr	0.49	0.18	0.19	0.16	0.12	0	0	0.16	0.23	0.21	0.01	0	0	0	0.83	0	0.22	0	0	0
H_{out}	nr	nr	nr	nr	1.9	0.7	0.7	0.6	0.5	0	0	0.6	0.9	0.8	4E-2	0	0	0	3.2	0	0.9	0	0	0
CH_{4out}	nr	nr	nr	nr	1.45	0.34	0.35	0.67	0.40	0.67	0.18	0.32	0.33	0.79	0.33	0.30	0.29	0.39	3.41	0.72	0.82	0.07	0.35	0.08
BE_{out}	nr	nr	nr	nr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$Feed_{out}$	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{out}	nr	nr	nr	nr	6.75	0.00	0.00	0.37	0.33	0.74	0.70	0.23	0.37	2.18	0.38	0.42	0.57	0.59	8.32	0.98	2.40	2.35	0.48	1.63
P_{out}	nr	nr	nr	nr	1.41	0.11	0.00	0.09	0.10	0.95	0.40	0.71	0.12	0.78	0.10	0.23	0.28	0.33	3.12	0.25	0.41	0.04	0.05	1.30
K_{out}	nr	nr	nr	nr	3.66	0.91	0.00	1.91	2.23	0.87	0.00	1.10	0.54	0.72	0.32	0.33	0.39	0.53	0.17	0.94	12.7	4.64	0.33	3.01

Table S21. Production of 1 MJ bioethanol. Mass and energy balances. Scenario BE5: C6 → BE, SF → Comb → CHP, Res → Feed. This scenario does not apply to household food waste, garden waste, and wood residues.

Parameter	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
$Mass_{in}$	nr	nr	nr	nr	nr	nr	nr	0.25	0.20	1.40	1.03	0.20	0.41	1.20	0.54	0.11	0.11	0.12	3.09	0.94	1.28	0.16	1.15	1.60
E_{in}	nr	nr	nr	nr	nr	nr	nr	0.07	0.06	0.04	0.02	0.05	0.07	0.07	0.02	0.00	0.00	0.01	0.25	0.04	0.09	2E-3	0.03	0.02
H_{in}	nr	nr	nr	nr	nr	nr	nr	1.2	1.0	1.0	0.5	1.7	2.0	1.8	0.2	0.4	0.4	0.4	4.7	0.9	1.6	0.4	0.4	1.0
E_{out}	nr	nr	nr	nr	nr	nr	nr	0.12	0.09	0	0	0.12	0.18	0.16	0.01	0	0	0	0.65	0	0.17	0	0	0
H_{out}	nr	nr	nr	nr	nr	nr	nr	1.3	0.9	0	0	1.2	1.8	1.7	0.1	0	0	0	6.6	0	1.8	0	0	0
CH_{4out}	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BE_{out}	nr	nr	nr	nr	nr	nr	nr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$Feed_{out}$	nr	nr	nr	nr	nr	nr	nr	0.06	0.03	0.3	0.02	0.03	0.03	0.07	0.03	0.04	0.04	0.05	0.31	0.21	0.06	0.07	0.13	0.05
N_{out}	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P_{out}	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K_{out}	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table S22. Production of 1 MJ bioethanol. Mass and energy balances. Scenario BE6: C6 → BE, SF → Syngas → CHP, Res → Feed. This scenario does not apply to household food waste, garden waste, and wood residues.

$Mass_{in}$	nr	nr	nr	nr	nr	nr	nr	0.25	0.20	1.40	1.03	0.20	0.41	1.20	0.54	0.11	0.11	0.12	3.09	0.94	1.28	0.16	1.15	1.60
E_{in}	nr	nr	nr	nr	nr	nr	nr	0.07	0.06	0.04	0.02	0.06	0.08	0.08	0.02	0.00	5E-3	5E-3	0.29	0.04	0.10	2E-3	0.03	0.02
H_{in}	nr	nr	nr	nr	nr	nr	nr	1.2	1.0	1.0	0.5	1.7	2.0	1.8	0.2	0.4	0.4	0.4	4.7	0.9	1.6	0.4	0.4	1.0
E_{out}	nr	nr	nr	nr	nr	nr	nr	0.16	0.12	0	0	0.16	0.23	0.21	0.01	0	0	0	0.83	0	0.22	0	0	0
H_{out}	nr	nr	nr	nr	nr	nr	nr	0.6	0.5	0	0	0.6	0.9	0.8	4E-2	0	0	0	3.2	0	0.9	0	0	0
CH_{4out}	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BE_{out}	nr	nr	nr	nr	nr	nr	nr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$Feed_{out}$	nr	nr	nr	nr	nr	nr	nr	0.06	0.03	0.3	0.02	0.03	0.03	0.07	0.03	0.04	0.04	0.05	0.31	0.21	0.06	0.07	0.13	0.05
N_{out}	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P_{out}	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K_{out}	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

3. GHG EFs: example of calculation

Examples are established for the case of biomethane production from household food waste. A similar calculation should be applied to all the remaining scenarios. Examples are established for both fossil and non-fossil energy system.

3.1 Biomethane production from household food waste (fossil energy system)

The total *GHG EF* is the sum of the following contributors: i) processing (*Process*), ii) energy co-products (*En.Cp*), iii) land-use changes (*LUC*), iv) avoided management (*Av.Man*), v) crop production (*Crop*), vi) fertilizer substitution (*Fertiliz*), vii) use on-land (*UOL*), and viii) transport (*Transp*). Sum of: *LUC, Av.Man*, *Crop*, and *Fertiliz* form the "induced effects". All the inputs and outputs should be expressed in relation to the functional unit, i.e. 1 MJ_{CH4}. Values are derived from mass/energy balances and GHG EFs detailed in Table S15 and Table S6. Eventual inconsistencies are due to rounding.

$$Process = E_{in} \cdot GHG\,EF_E + H_{in} \cdot GHG\,EF_H + F_{in} \cdot GHG\,EF_F + GHG_{fug.emissions}$$
$$= 0.035 \cdot 977 + 0.47 \cdot 64 + 0.012 \cdot 79 + 1\% \cdot \frac{0.714}{38} \cdot 10^3 \cdot 25 = 72\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$En.Cp. = E_{out} \cdot (-GHG\,EF_E) + H_{out} \cdot (-GHG\,EF_H) + Feed_{out} \cdot (-GHG\,EF_{Feed})$$
$$= 0.05 \cdot (-977) + 0.46 \cdot (-64) + 0 = -74\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$LUC = 0$$

$$Av.Man = -140\ \frac{g\,CO_2 - eq}{kg\,ww_{HFW}} \cdot 0.39 \frac{kg\,ww_{HFW}}{MJ_{CH4}} = -54\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$ → see section 1.6

$$Crop = 0$$

$$Fertiliz = N_{out} \cdot SE_N \cdot (-GHG\,EF_N) + P_{out} \cdot SE_P \cdot (-GHG\,EF_P) + K_{out} \cdot SE_K \cdot (-GHG\,EF_K) - Av.Leach.$$
$$= 1.78 \cdot 75\% \cdot (-2.6) + 0.38 \cdot 71\% \cdot (-1.4 \cdot \frac{142}{62}) + 0.98 \cdot 76\% \cdot (-0.38 \cdot \frac{94}{78}) - 11 = -16\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$UOL = N_{out} \cdot 1.5\% \cdot \frac{44}{28} \cdot 298 + (N_{out} \cdot 51\% + N_{out} \cdot 1.1\%) \cdot 0.75\% \cdot \frac{44}{28} \cdot 298 + C_{seq} \cdot (-44/12)$$
$$= 13 + 3.3 - 3.3 = 13\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$Transp = Biomass_{in} \cdot TD \cdot GHG\,EF_T + Digestate_{out} \cdot TD \cdot GHG\,EF_T + SF_{out} \cdot TD \cdot GHG\,EF_T$$
$$= 0.39 \cdot 30 \cdot 75 \cdot 10^{-3} + 0.8 \cdot 30 \cdot 75 \cdot 10^{-3} + 0.02 \cdot 200 \cdot 75 \cdot 10^{-3} = 3\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$GHG\,EF = Process + En.Cp + (LUC + Av.Man + Crop + Fertiliz) + UOL + Transp$$
$$= 72 - 74 + (0 - 54 + 0 - 16) + 13 + 3 = -56\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

Av.Leach:* Avoided leaching from displaced mineral N-fertilizer (g CO_2-eq $MJ^{-1}{}_{CH4}$)

$Biomass_{in}$: Biomass input to the process (kg_{ww} $MJ^{-1}{}_{CH4}$)

$Digestate_{out}$: digestate output from the process (kg_{ww} $MJ^{-1}{}_{CH4}$); equals 0.08 kg_{ww} $MJ^{-1}{}_{CH4}$

E_{in}: electricity input to the process (kWh $MJ^{-1}{}_{CH4}$)

E_{out}: electricity output from the process (kWh $MJ^{-1}{}_{CH4}$)

$GHG_{fug.emission}$: fugitive emissions (g CO_2-eq $MJ^{-1}{}_{CH4}$); assumed 1%CH_4 generated (Table S4)

F_{in}: fuel input to the process (MJ $MJ^{-1}{}_{CH4}$)

$Feed_{out}$: feed output from the process (SFU $MJ^{-1}{}_{CH4}$ and/or kg protein $MJ^{-1}{}_{CH4}$)

H_{in}: heat input to the process (MJ $MJ^{-1}{}_{CH4}$)

H_{out}: heat output from the process (MJ $MJ^{-1}{}_{CH4}$)

K_{out}: potassium content of the residual digestate (kg K $MJ^{-1}{}_{CH4}$)

N_{out}: nitrogen content of the residual digestate (kg N $MJ^{-1}{}_{CH4}$)

P_{out}: phosphorous content of the residual digestate (kg P $MJ^{-1}{}_{CH4}$)

SF_{out}: solid fraction output from the process (kg_{ww} $MJ^{-1}{}_{CH4}$); equals 0.02 kg_{ww} $MJ^{-1}{}_{CH4}$

SE_N: substitution efficiency for N (75%) following legislation

SE_P: substitution efficiency for P (71%) following approach described in Tonini et al. (2015)

SE_K: substitution efficiency for K (76%) following approach described in Tonini et al. (2015)

TD: transport distance (km); see section 1.9 of this document

$GHG\ EF_E$: GHG EF of (marginal) electricity production (g CO_2-eq kWh^{-1})

$GHG\ EF_H$: GHG EF of (marginal) heat production (g CO_2-eq MJ^{-1})

$GHG\ EF_F$: GHG EF of (marginal) feed production (g CO_2-eq kg^{-1})

$GHG\ EF_N$: GHG EF of (marginal) mineral N-fertilizer production (g CO_2-eq kg N^{-1})

$GHG\ EF_P$: GHG EF of (marginal) mineral P-fertilizer production (g CO_2-eq kg P^{-1})

$GHG\ EF_K$: GHG EF of (marginal) mineral K-fertilizer production (g CO_2-eq kg K^{-1})

$GHG\ EF_T$: GHG EF of material transport in trucks (g CO_2-eq $kg_{ww}km^{-1}$)

38: LHV of CH_4 (MJ/Nm^3 CH_4); 25: GWP of CH_4; 0.714: density of CH_4 (kg L^{-1}); 142: molecular weight (MW) of P_2O_5; 62: MW of P_2; 78: MW of K_2; 94: MW of K_2O; 44: MW of CO_2 and N_2O; 28: MW of N_2; 12: MW of C.

$$*Av.Leach. = N_{out} \cdot SF_N \cdot 1.5\% \cdot \frac{44}{28} \cdot 298 + (N_{out} \cdot SF_N \cdot 20\% + N_{out} \cdot SF_N \cdot 1.1\%) \cdot 0.75\% \cdot \frac{44}{28} \cdot 298 = 11\,g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

3.2 Biomethane production from household food waste (non-fossil energy system)

$$Process = E_{in} \cdot GHG\,EF_E + H_{in} \cdot GHG\,EF_H + F_{in} \cdot GHG\,EF_F + GHG_{fug.emissions}$$
$$= 0.035 \cdot 19 + 0.47 \cdot 19.2 + 0.012 \cdot 79 + 1\% \cdot \frac{0.714}{38} \cdot 10^3 \cdot 25 = 15\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$En.Cp. = E_{out} \cdot (-GHG\,EF_E) + H_{out} \cdot (-GHG\,EF_H) + Feed_{out} \cdot (-GHG\,EF_{Feed})$$
$$= 0.05 \cdot (-19) + 0.46 \cdot (-19.2) + 0 = -10\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$LUC = 0$$

$$Av.Man = 200\ \frac{g\,CO_2 - eq}{kg\,ww_{HFW}} \cdot 0.39 \frac{kg\,ww_{HFW}}{MJ_{CH4}} = 77\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$Crop = 0$$

$$Fertiliz = N_{out} \cdot SE_N \cdot (-GHG\,EF_N) + P_{out} \cdot SE_P \cdot (-GHG\,EF_P) + K_{out} \cdot SE_K \cdot (-GHG\,EF_K) - Av.Leach.$$
$$= 1.78 \cdot 75\% \cdot (-2.6) + 0.38 \cdot 71\% \cdot (-1.4 \cdot \frac{142}{62}) + 0.98 \cdot 76\% \cdot (-0.38 \cdot \frac{94}{78}) - 11 = -16\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$UOL = N_{out} \cdot 1.5\% \cdot \frac{44}{28} \cdot 298 + (N_{out} \cdot 51\% + N_{out} \cdot 1.1\%) \cdot 0.75\% \cdot \frac{44}{28} \cdot 298 + C_{seq} \cdot (-44/12)$$
$$= 13 + 3.3 - 3.3 = 13\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$Transp = Biomass_{in} \cdot TD \cdot GHG\,EF_T + Digestate_{out} \cdot TD \cdot GHG\,EF_T + SF_{out} \cdot TD \cdot GHG\,EF_T$$
$$= 0.39 \cdot 30 \cdot 75 \cdot 10^{-3} + 0.8 \cdot 30 \cdot 75 \cdot 10^{-3} + 0.02 \cdot 200 \cdot 75 \cdot 10^{-3} = 3\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

$$GHG\,EF = Process + En.Cp + (LUC + Av.Man + Crop + Fertiliz) + UOL + Transp$$
$$= 15 - 10 + (0 + 77 + 0 - 16) + 13 + 3 = 82\ g\,CO_2 - eq\,MJ^{-1}{}_{CH4}$$

4. GHG EFs: breakdown of the impact contributions

Table S23-S35 provides the detailed GHG breakdown of the impact contributions for production of bioelectricity (Table S23-S26), biomethane (S27-S29), and bioethanol (S30-S35). The sum of “LUC” (land use changes), “Av. Man” (avoided management, i.e. counterfactual), “Crop” (crop cultivation), and “Fertiliz” (fertilizers substitution) constitute the “induced effects” shown in Figure 4 of the manuscript.

4.1 GHG EFs for production of bioelectricity (1 kWh)

Table S23. GHG EFs (g CO_2 kWh[1]). Bel1: Combustion → CHP. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport. Note that, for household food waste, this scenario is not applicable as it represents its reference counterfactual management (Table 2 of the manuscript).

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	2082	1366	435	1780	nr	345	225	224	246	923	2080	214	332	812	1019	239	244	244	619	777	862	308	1341	2844
En. Cp	-650	-650	-650	-650	nr	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650	-650
LUC	0	0	0	0	nr	0	0	0	0	0	0	309	226	227	292	719	553	757	794	957	1018	1210	1043	1239
Av.Man	-556	-422	0	-383	nr	-134	41	77	83	78	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	nr	0	0	0	0	0	0	-15	49	392	259	105	466	696	188	296	272	356	341	387
Fertiliz.	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	18	12	3	15	nr	12	7	7	8	34	78	7	11	30	17	4	4	4	60	87	85	92	108	122
Net	893	308	-212	761	nr	-425	-376	-340	-316	387	1508	-136	-32	812	935	418	617	1051	1011	1468	1589	1317	2183	3942
Non-fossil energy system																								
Process	575	356	60	473	nr	35	10	6	5	209	538	4	44	185	234	7	7	7	132	164	188	14	333	791
En. Cp	-197	-196	-197	-197	nr	-196	-196	-196	-197	-196	-197	-197	-197	-196	-197	-196	-197	-197	-197	-197	-196	-197	-197	-196
LUC	0	0	0	0	nr	0	0	0	0	0	0	309	226	227	292	719	553	757	794	957	1018	1210	1043	1239
Av.Man	-569	-434	0	-241	nr	-79	24	77	83	78	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	nr	0	0	0	0	0	0	-15	49	392	259	105	466	696	188	296	272	356	341	387
Fertiliz.	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	0	0	0	0	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	15	10	3	13	nr	10	6	6	6	28	64	6	9	24	14	3	3	3	58	85	82	92	104	117
Net	-175	-264	-134	47	nr	-230	-156	-107	-104	119	405	107	132	632	602	637	832	1266	976	1306	1364	1476	1624	2337

Table S24. GHG EFs (g CO_2 kWh^{1}). Bel2: Syngas → CHP. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land-use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	1661	1109	399	1423	205	328	228	232	254	770	1660	222	307	681	838	246	250	250	530	660	730	307	1086	2242
En. Cp	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246	-246
LUC	0	0	0	0	0	0	0	0	0	0	0	237	172	174	222	551	425	577	610	734	782	922	801	955
Av.Man	-430	-325	0	-293	-273	-102	31	60	63	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-11	38	300	196	80	356	530	144	228	208	271	262	298
Fertiliz.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	14	9	3	12	7	9	6	6	6	26	59	5	9	23	13	3	3	3	46	67	65	70	82	94
Net	1000	547	155	896	-307	-11	18	51	76	609	1473	207	279	932	1023	634	788	1114	1084	1443	1540	1325	1985	3343
Non-fossil energy system																								
Process	445	275	47	362	4	28	9	6	5	160	410	4	34	143	179	7	6	6	103	127	146	12	254	607
En. Cp	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74	-74
LUC	0	0	0	0	0	0	0	0	0	0	0	237	172	174	222	551	425	577	610	734	782	922	801	955
Av.Man	-439	-335	0	-184	429	-60	18	60	63	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-11	38	300	196	80	356	530	144	228	208	271	262	298
Fertiliz.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	11	7	2	10	6	7	5	5	5	21	49	4	7	19	11	2	2	2	45	65	63	70	79	90
Net	-57	-126	-25	113	364	-99	-43	-5	-2	166	384	160	176	562	533	566	715	1042	827	1080	1125	1202	1322	1876

Table S25. GHG EFs (g CO_2 kWh^{1}). Bel3: Biogas → CHP, SF → Comb → CHP. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	422	442	405	259	377	486	373	377	380	234	264	386	385	388	413	211	212	212	347	229	431	213	246	288
En. Cp	-336	-394	-280	-231	-341	-379	-379	-329	-281	-231	-231	-370	-396	-317	-264	-231	-231	-230	-304	-231	-282	-231	-231	-231
LUC	0	0	0	0	0	0	0	0	0	0	0	281	209	202	241	601	470	643	710	849	877	960	884	990
Av.Man	-505	-400	0	-321	-318	-123	37	69	70	68	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-13	46	348	212	88	395	591	169	263	234	282	289	309
Fertiliz.	-319	-250	-198	-407	-91	-20	-5	-26	-29	-52	-139	-20	-26	-132	-59	-82	-114	-107	-148	-83	-139	-127	-64	-94
UOL	314	242	183	402	73	-2	-18	2	4	20	122	-3	5	116	36	55	87	81	131	51	120	110	33	75
Transp.	28	25	22	29	20	30	18	21	24	49	90	20	22	40	32	18	19	20	65	98	93	94	110	113
Net	-395	-334	133	-268	-279	-8	27	114	167	89	106	280	244	644	612	661	838	1208	971	1175	1333	1300	1267	1449
Non-fossil energy system																								
Process	89	98	82	36	76	110	76	75	74	29	38	80	81	78	83	22	22	22	65	27	89	22	32	45
En. Cp	-102	-119	-85	-70	-103	-115	-115	-100	-85	-70	-70	-112	-120	-96	-80	-70	-70	-70	-92	-70	-85	-70	-70	-70
LUC	0	0	0	0	0	0	0	0	0	0	0	281	209	202	241	601	470	643	710	849	877	960	884	990
Av.Man	-517	-411	0	-202	247	-72	22	69	70	68	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-13	46	348	212	88	395	591	169	263	234	282	289	309
Fertiliz.	-319	-250	-198	-407	-91	-20	-5	-26	-29	-52	-139	-20	-26	-132	-59	-82	-114	-107	-148	-83	-139	-127	-64	-94
UOL	314	242	183	402	73	-2	-18	2	4	20	122	-3	5	116	36	55	87	81	131	51	120	110	33	75
Transp.	23	20	18	24	17	25	15	17	19	40	74	16	18	33	27	15	16	16	61	92	87	90	103	107
Net	-511	-419	1	-216	219	-74	-25	38	53	36	24	229	213	549	460	629	806	1176	897	1129	1182	1267	1208	1361

Table S26. GHG EFs (g CO_2 kWh^{1}). Bel4: Biogas → CHP, SF → Syn → CHP. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	411	413	396	256	364	504	354	366	377	234	267	355	358	382	416	212	211	209	337	228	415	213	244	289
En. Cp	-217	-219	-207	-213	-217	-212	-218	-225	-209	-214	-209	-217	-219	-214	-210	-214	-219	-209	-214	-207	-213	-218	-215	-217
LUC	0	0	0	0	0	0	0	0	0	0	0	249	186	196	236	592	471	617	655	840	837	958	876	1012
Av.Man	-481	-355	0	-316	-296	-110	33	65	68	66	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-12	40	338	208	87	393	562	154	260	223	282	287	317
Fertiliz.	-303	-219	-189	-400	-85	-18	-5	-24	-28	-50	-142	-18	-23	-128	-58	-81	-113	-103	-137	-82	-132	-127	-63	-96
UOL	289	231	171	396	69	-1	-16	4	6	25	117	-1	5	125	36	50	101	82	130	51	121	115	34	77
Transp.	27	22	22	29	19	27	16	19	23	47	92	17	19	39	32	18	19	18	59	96	88	93	109	115
Net	-273	-128	192	-249	-145	190	165	205	237	109	125	373	366	739	660	664	862	1176	983	1187	1339	1316	1272	1497
Non-fossil energy system																								
Process	86	89	80	36	72	116	71	71	74	29	38	71	72	76	84	22	22	22	63	27	84	22	32	45
En. Cp	-66	-66	-63	-65	-66	-64	-66	-68	-63	-65	-63	-66	-66	-65	-64	-65	-66	-63	-65	-63	-64	-66	-65	-66
LUC	0	0	0	0	0	0	0	0	0	0	0	249	186	196	236	592	471	617	655	840	837	958	876	1012
Av.Man	-492	-365	0	-199	422	-65	20	65	68	66	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-12	40	338	208	87	393	562	154	260	223	282	287	317
Fertiliz.	-303	-219	-189	-400	-85	-18	-5	-24	-28	-50	-142	-18	-23	-128	-58	-81	-113	-103	-137	-82	-132	-127	-63	-96
UOL	289	231	171	396	69	-1	-16	4	6	25	117	-1	5	125	36	50	101	82	130	51	121	115	34	77
Transp.	22	18	18	24	15	22	13	16	19	39	76	14	16	32	26	15	16	15	56	91	83	89	102	109
Net	-463	-313	16	-208	428	-10	17	63	76	44	26	238	230	575	469	620	823	1131	856	1125	1151	1275	1203	1398

4.2 GHG EFs for production of biomethane (1 MJ)

Table S27. GHG EFs (g CO_2 MJ^{1}). BM1: Syngas → CH_4. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	290	202	84	253	52	73	55	56	59	145	294	54	68	130	157	58	59	60	105	125	135	68	198	389
En. Cp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LUC	0	0	0	0	0	0	0	0	0	0	0	39	29	29	37	91	70	95	100	120	126	151	131	156
Av.Man	-70	-54	0	-49	-45	-17	5	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-2	6	49	32	13	59	88	24	37	34	44	43	49
Fertiliz.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	4	3	2	4	3	3	2	3	3	6	12	2	3	5	4	2	2	2	9	13	12	14	15	17
Net	223	151	86	208	9	59	63	68	72	160	306	94	106	213	230	164	190	246	238	295	308	277	387	611
Non-fossil energy system																								
Process	73	46	8	60	1	5	2	1	1	27	68	1	6	24	30	1	1	1	17	21	24	2	42	101
En. Cp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LUC	0	0	0	0	0	0	0	0	0	0	0	39	29	29	37	91	70	95	100	120	126	151	131	156
Av.Man	-72	-56	0	-31	64	-10	3	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-2	6	49	32	13	59	88	24	37	34	44	43	49
Fertiliz.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	3	2	2	3	2	3	2	2	2	5	10	2	2	4	3	2	2	2	9	12	12	13	15	16
Net	4	-7	10	33	67	-2	7	13	14	42	79	40	43	106	102	107	132	187	150	190	196	211	231	322

Table S28. GHG EFs (g CO_2 MJ^{1}). BM2: Biogas → CH_4, SF → Comb → CHP. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	77	97	67	42	72	105	83	70	64	38	42	80	89	72	64	36	36	36	63	38	71	36	40	45
En. Cp	-67	-126	-27	0	-74	-112	-114	-60	-28	0	0	-100	-131	-54	-17	0	0	0	-43	0	-29	0	0	0
LUC	0	0	0	0	0	0	0	0	0	0	0	53	43	32	32	76	58	78	107	105	126	121	112	123
Av.Man	-83	-80	0	-40	-54	-24	7	11	10	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-2	9	56	28	11	49	71	25	32	33	36	37	38
Fertiliz.	-52	-49	-28	-51	-16	-4	-1	-4	-4	-6	-17	-4	-5	-21	-8	-10	-14	-13	-22	-10	-20	-16	-8	-12
UOL	54	50	24	51	13	-1	-4	1	0	2	15	0	2	19	5	7	11	10	20	7	18	14	4	9
Transp.	5	5	3	4	3	6	4	3	3	6	11	4	5	6	4	2	2	2	10	12	13	12	14	14
Net	-67	-104	40	5	-56	-30	-25	20	46	49	51	30	10	109	108	121	142	184	158	184	212	203	199	218
Non-fossil energy system																								
Process	16	21	14	7	15	23	17	14	13	6	7	16	18	15	13	5	5	5	12	6	15	6	7	8
En. Cp	-9	-17	-4	0	-10	-15	-15	-8	-4	0	0	-13	-17	-7	-2	0	0	0	-6	0	-4	0	0	0
LUC	0	0	0	0	0	0	0	0	0	0	0	53	43	32	32	76	58	78	107	105	126	121	112	123
Av.Man	-85	-82	0	-25	77	-14	4	11	10	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-2	9	56	28	11	49	71	25	32	33	36	37	38
Fertiliz.	-52	-49	-28	-51	-16	-4	-1	-4	-4	-6	-17	-4	-5	-21	-8	-10	-14	-13	-22	-10	-20	-16	-8	-12
UOL	54	50	24	51	13	-1	-4	1	0	2	15	0	2	19	5	7	11	10	20	7	18	14	4	9
Transp.	4	4	3	3	3	5	3	3	3	5	9	3	4	5	3	2	2	2	9	11	12	11	13	13
Net	-72	-74	9	-15	82	-5	4	16	18	16	14	52	53	98	71	91	111	153	145	151	180	172	164	181

Table S29. GHG EFs (g CO_2 MJ^{1}). BM3: Biogas → CH_4, SF → Syn → CHP. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	79	101	68	42	74	108	87	72	65	38	42	84	93	74	65	36	36	36	64	38	72	36	40	45
En. Cp	-61	-118	-23	0	-68	-103	-107	-56	-24	0	0	-93	-122	-49	-15	0	0	0	-39	0	-27	0	0	0
LUC	0	0	0	0	0	0	0	0	0	0	0	53	43	32	32	76	58	78	107	105	126	121	112	123
Av.Man	-83	-80	0	-40	-54	-24	7	11	10	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-2	9	56	28	11	49	71	25	32	33	36	37	38
Fertiliz.	-52	-49	-28	-51	-16	-4	-1	-4	-4	-6	-17	-4	-5	-21	-8	-10	-14	-13	-22	-10	-20	-16	-8	-12
UOL	54	50	24	51	13	-1	-4	1	0	2	15	0	2	19	5	7	11	10	20	7	18	14	4	9
Transp.	5	5	3	4	3	6	4	3	3	6	11	4	5	6	4	2	2	2	10	12	13	12	14	14
Net	-58	-92	44	5	-46	-17	-14	27	50	49	51	40	24	116	111	121	142	184	164	184	215	203	199	218
Non-fossil energy system																								
Process	16	21	14	7	15	23	17	14	13	6	7	16	18	15	13	5	5	5	12	6	15	6	7	8
En. Cp	-4	-8	-1	0	-4	-7	-7	-4	-1	0	0	-6	-8	-3	-1	0	0	0	-2	0	-2	0	0	0
LUC	0	0	0	0	0	0	0	0	0	0	0	53	43	32	32	76	58	78	107	105	126	121	112	123
Av.Man	-85	-82	0	-25	77	-14	4	11	10	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	0	0	0	0	0	0	0	0	0	0	0	-2	9	56	28	11	49	71	25	32	33	36	37	38
Fertiliz.	-52	-49	-28	-51	-16	-4	-1	-4	-4	-6	-17	-4	-5	-21	-8	-10	-14	-13	-22	-10	-20	-16	-8	-12
UOL	54	50	24	51	13	-1	-4	1	0	2	15	0	2	19	5	7	11	10	20	7	18	14	4	9
Transp.	4	4	3	3	3	5	3	3	3	5	9	3	4	5	3	2	2	2	9	11	12	11	13	13
Net	-67	-65	12	-15	87	3	12	21	21	16	14	59	62	102	73	91	111	153	149	151	183	172	164	181

4.3 GHG EFs for production of bioethanol (1 MJ)

Table S30. GHG EFs (g CO_2 MJ^{1}). BE1: C6 → BE, SF → Comb → CHP, Res → Biogas → CHP. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	nr	nr	nr	nr	382	236	214	182	150	167	86	193	228	241	41	38	44	50	720	149	259	47	89	88
En. Cp	nr	nr	nr	nr	-827	-285	-291	-304	-212	-102	-27	-247	-344	-384	-63	-46	-44	-58	-1566	-108	-407	-10	-53	-13
LUC	nr	nr	nr	nr	0	0	0	0	0	0	0	72	66	75	34	82	63	95	887	259	339	155	198	150
Av.Man	nr	nr	nr	nr	-205	-34	11	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	0	0	0	0	0	0	0	-3	14	129	30	12	53	88	211	80	90	46	65	47
Fertiliz	nr	nr	nr	nr	-59	0	0	-3	-3	-6	-6	-2	-3	-19	-3	-4	-5	-5	-73	-9	-21	-21	-4	-14
UOL	nr	nr	nr	nr	56	-2	-2	0	1	4	6	0	1	17	2	3	4	4	63	6	19	21	3	15
Transp.	nr	nr	nr	nr	13	8	5	6	5	24	12	5	7	15	4	2	2	3	82	33	35	16	27	17
Net	nr	nr	nr	nr	-639	-77	-64	-97	-41	113	71	18	-31	74	45	87	118	176	324	411	314	254	325	290
Non-fossil energy system																								
Process	nr	nr	nr	nr	59	44	39	28	24	24	12	37	41	38	5	12	12	14	101	23	35	14	11	22
En. Cp	nr	nr	nr	nr	-97	-35	-35	-34	-25	-7	-2	-30	-43	-44	-5	-3	-3	-4	-177	-8	-47	-1	-4	-1
LUC	nr	nr	nr	nr	0	0	0	0	0	0	0	72	66	75	34	82	63	95	887	259	339	155	198	150
Av.Man	nr	nr	nr	nr	292	-20	6	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	0	0	0	0	0	0	0	-3	14	129	30	12	53	88	211	80	90	46	65	47
Fertiliz	nr	nr	nr	nr	-59	0	0	-3	-3	-6	-6	-2	-3	-19	-3	-4	-5	-5	-73	-9	-21	-21	-4	-14
UOL	nr	nr	nr	nr	56	-2	-2	0	1	4	6	0	1	17	2	3	4	4	63	6	19	21	3	15
Transp.	nr	nr	nr	nr	10	7	4	5	4	20	10	4	6	12	3	2	2	2	77	31	33	15	25	16
Net	nr	nr	nr	nr	262	-6	12	18	19	60	20	78	82	208	66	103	127	193	1089	383	449	230	294	235

Table S31. GHG EFs (g CO_2 MJ^{1}). BE2: C6 → BE, SF → Comb → CHP, Res → Biogas → CH_4. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	nr	nr	nr	nr	382	236	210	180	150	164	87	193	229	244	40	37	44	49	713	147	258	46	88	84
En. Cp	nr	nr	nr	nr	-728	-264	-265	-256	-184	-54	-14	-225	-320	-332	-39	-24	-24	-31	-1314	-56	-345	-5	-28	-6
LUC	nr	nr	nr	nr	0	0	0	0	0	0	0	87	78	51	34	81	64	96	888	258	338	155	198	150
Av.Man	nr	nr	nr	nr	-205	-35	11	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	0	0	0	0	0	0	0	-3	14	129	30	12	53	88	211	80	90	46	65	47
Fertiliz	nr	nr	nr	nr	-59	0	0	-3	-3	-6	-6	-2	-3	-19	-3	-4	-5	-5	-73	-9	-21	-21	-4	-14
UOL	nr	nr	nr	nr	56	-2	-2	0	1	4	6	0	1	17	2	3	4	4	65	6	18	21	3	15
Transp.	nr	nr	nr	nr	13	8	5	6	5	24	12	5	7	15	4	2	2	3	82	33	35	16	27	17
Net	nr	nr	nr	nr	-540	-57	-41	-50	-13	158	84	54	6	105	68	108	138	204	572	460	373	256	350	292
Non-fossil energy system																								
Process	nr	nr	nr	nr	65	43	39	28	24	24	13	36	42	41	5	9	9	10	115	23	38	8	11	21
En. Cp	nr	nr	nr	nr	-174	-54	-54	-70	-46	-44	-12	-47	-60	-87	-23	-19	-20	-25	-363	-46	-91	-4	-23	-5
LUC	nr	nr	nr	nr	0	0	0	0	0	0	0	72	66	75	34	81	64	96	888	258	338	154	199	150
Av.Man	nr	nr	nr	nr	292	-21	6	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	0	0	0	0	0	0	0	-3	14	129	30	12	53	88	211	80	90	45	65	47
Fertiliz	nr	nr	nr	nr	-59	0	0	-3	-3	-6	-6	-2	-3	-19	-3	-4	-5	-5	-73	-9	-21	-21	-4	-14
UOL	nr	nr	nr	nr	56	-2	-2	0	1	4	6	0	1	17	2	3	4	4	65	6	18	21	3	15
Transp.	nr	nr	nr	nr	10	7	4	5	4	20	10	4	6	12	3	2	2	2	77	31	33	15	25	16
Net	nr	nr	nr	nr	191	-26	-7	-18	-3	24	10	60	66	169	49	83	107	170	920	344	406	218	276	229

Table S32. GHG EFs (g CO_2 MJ^{1}). BE3: C6 → BE, SF → Syn → CHP, Res → Biogas → CHP. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	nr	nr	nr	nr	407	248	221	191	160	167	88	202	241	257	41	38	44	50	759	150	274	47	90	88
En. Cp	nr	nr	nr	nr	-805	-283	-284	-297	-209	-103	-28	-240	-334	-379	-63	-45	-46	-59	-1518	-107	-395	-10	-54	-12
LUC	nr	nr	nr	nr	0	0	0	0	0	0	0	72	66	75	34	81	63	96	881	258	338	155	198	150
Av.Man	nr	nr	nr	nr	-205	-35	11	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	0	0	0	0	0	0	0	-3	14	129	30	12	53	88	209	80	90	46	65	47
Fertiliz	nr	nr	nr	nr	-59	0	0	-3	-3	-7	-6	-2	-3	-19	-3	-4	-5	-5	-71	-8	-21	-21	-4	-14
UOL	nr	nr	nr	nr	56	-2	-2	0	1	4	6	0	1	17	2	3	4	4	65	6	18	21	3	15
Transp.	nr	nr	nr	nr	13	8	5	6	5	24	12	5	7	15	4	2	2	3	81	33	35	16	27	17
Net	nr	nr	nr	nr	-593	-64	-49	-81	-29	111	72	33	-8	95	45	87	117	176	406	412	340	251	326	290
Non-fossil energy system																								
Process	nr	nr	nr	nr	59	43	38	27	23	23	12	36	41	39	4	10	10	11	101	22	36	11	11	22
En. Cp	nr	nr	nr	nr	-61	-22	-22	-22	-16	-8	-2	-18	-25	-29	-5	-3	-3	-4	-115	-8	-30	-1	-4	-1
LUC	nr	nr	nr	nr	0	0	0	0	0	0	0	72	66	75	34	81	63	96	881	258	338	154	199	150
Av.Man	nr	nr	nr	nr	292	-21	6	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	0	0	0	0	0	0	0	-3	14	129	30	12	53	88	209	80	90	45	65	47
Fertiliz	nr	nr	nr	nr	-59	0	0	-3	-3	-7	-6	-2	-3	-19	-3	-4	-5	-5	-71	-8	-21	-21	-4	-14
UOL	nr	nr	nr	nr	56	-2	-2	0	1	4	6	0	1	17	2	3	4	4	65	6	18	21	3	15
Transp.	nr	nr	nr	nr	10	7	4	5	4	20	10	4	6	12	3	2	2	2	76	31	33	15	25	16
Net	nr	nr	nr	nr	298	6	25	29	27	58	20	88	100	224	66	100	124	192	1146	381	465	224	295	234

Table S33. GHG EFs (g CO_2 MJ^1). BE4: C6 → BE, SF → Syn → CHP, Res → Biogas → CH_4. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	nr	nr	nr	nr	405	247	221	190	159	164	87	201	240	256	40	37	44	49	755	148	273	46	88	84
En. Cp	nr	nr	nr	nr	-702	-258	-260	-249	-180	-54	-14	-217	-311	-321	-39	-24	-24	-31	-1270	-56	-335	-5	-28	-6
LUC	nr	nr	nr	nr	0	0	0	0	0	0	0	72	66	75	34	81	63	96	881	258	338	155	198	150
Av.Man	nr	nr	nr	nr	-205	-35	11	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	0	0	0	0	0	0	0	-3	14	129	30	12	53	88	209	80	90	46	65	47
Fertiliz	nr	nr	nr	nr	-59	0	0	-3	-3	-7	-6	-2	-3	-19	-3	-4	-5	-5	-71	-8	-21	-21	-4	-14
UOL	nr	nr	nr	nr	56	-2	-2	0	1	4	6	0	1	17	2	3	4	4	65	6	18	21	3	15
Transp.	nr	nr	nr	nr	13	8	5	6	5	24	12	5	7	15	4	2	2	3	81	33	35	16	27	17
Net	nr	nr	nr	nr	-492	-40	-25	-33	-1	158	85	55	15	151	68	108	138	204	650	461	399	255	350	292
Non-fossil energy system																								
Process	nr	nr	nr	nr	65	44	39	29	24	24	13	36	42	42	5	9	9	10	115	23	39	8	11	21
En. Cp	nr	nr	nr	nr	-137	-40	-40	-58	-37	-44	-12	-35	-43	-71	-22	-19	-20	-25	-298	-46	-74	-4	-23	-5
LUC	nr	nr	nr	nr	0	0	0	0	0	0	0	72	66	75	34	81	63	96	881	258	338	154	199	150
Av.Man	nr	nr	nr	nr	292	-21	6	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	0	0	0	0	0	0	0	-3	14	129	30	12	53	88	209	80	90	45	65	47
Fertiliz	nr	nr	nr	nr	-59	0	0	-3	-3	-7	-6	-2	-3	-19	-3	-4	-5	-5	-71	-8	-21	-21	-4	-14
UOL	nr	nr	nr	nr	56	-2	-2	0	1	4	6	0	1	17	2	3	4	4	65	6	18	21	3	15
Transp.	nr	nr	nr	nr	10	7	4	5	4	20	10	4	6	12	3	2	2	2	76	31	33	15	25	16
Net	nr	nr	nr	nr	228	-12	8	-6	7	23	10	72	83	185	50	83	107	170	978	344	423	218	276	229

Table S34. GHG EFs (g CO_2 MJ^{1}). BE5: C6 → BE, SF → Comb → CHP, Res → Feed. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport. It is assumed that this scenario, where feed is produced from the input-biomass, is not applicable to household food waste, garden waste, and wood residues due to hygienic/technical limitations.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	nr	nr	nr	nr	nr	nr	nr	164	139	147	81	184	219	220	40	30	36	39	629	129	236	45	79	82
En. Cp	nr	nr	nr	nr	nr	nr	nr	-203	-151	0	0	-199	-295	-265	-14	0	0	0	-1051	0	-283	0	0	0
LUC	nr	nr	nr	nr	nr	nr	nr	-71	-41	-287	-32	72	66	75	0	37	15	35	435	26	243	79	48	103
Av.Man	nr	nr	nr	nr	nr	nr	nr	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	nr	nr	nr	-24	-13	-100	-8	-15	1	102	19	-2	38	69	84	1	66	18	13	30
Fertiliz	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	nr	nr	nr	nr	nr	nr	nr	-2	0	-13	7	1	2	5	0	-3	-3	-4	43	5	25	6	8	11
Net	nr	nr	nr	nr	nr	nr	nr	-115	-49	-226	48	43	-6	137	46	61	87	139	140	160	288	147	148	225
Non-fossil energy system																								
Process	nr	nr	nr	nr	nr	nr	nr	25	22	21	11	34	40	37	4	7	7	8	98	19	34	8	9	20
En. Cp	nr	nr	nr	nr	nr	nr	nr	-27	-20	0	0	-26	-39	-35	-2	0	0	0	-139	0	-38	0	0	0
LUC	nr	nr	nr	nr	nr	nr	nr	-71	-41	-287	-32	72	66	75	0	37	15	35	435	26	243	79	48	103
Av.Man	nr	nr	nr	nr	nr	nr	nr	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	nr	nr	nr	-24	-13	-100	-8	-15	1	102	19	-2	38	69	84	1	66	18	13	30
Fertiliz	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	nr	nr	nr	nr	nr	nr	nr	-2	0	-15	5	0	1	3	-1	-3	-3	-4	40	4	23	6	7	10
Net	nr	nr	nr	nr	nr	nr	nr	-78	-36	-354	-23	65	69	181	21	39	58	107	517	50	329	110	77	163

Table S35. GHG EFs (g CO_2 MJ^{1}). BE6: C6 → BE, SF → Syn → CHP, Res → Feed. Fossil and non-fossil energy system. Process: processing; En. Cp: energy coproducts; LUC: land use changes; Av. Man: avoided management (counterfactual); Crop: crop cultivation; Fertiliz: fertilizers substitution; UOL: use on-land; Transp: transport. It is assumed that this scenario, where feed is produced from the input-biomass, is not applicable to household food waste, garden waste, and wood residues due to hygienic/technical limitations.

Process	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Fossil energy system																								
Process	nr	nr	nr	nr	nr	nr	nr	174	147	147	81	193	231	232	40	30	36	39	675	129	251	45	79	82
En. Cp	nr	nr	nr	nr	nr	nr	nr	-197	-145	0	0	-192	-283	-255	-13	0	0	0	-1015	0	-273	0	0	0
LUC	nr	nr	nr	nr	nr	nr	nr	-71	-41	-287	-32	72	66	75	0	37	15	35	435	26	243	79	48	103
Av.Man	nr	nr	nr	nr	nr	nr	nr	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	nr	nr	nr	-24	-13	-100	-8	-15	1	102	19	-2	38	69	84	1	66	18	13	30
Fertiliz	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	nr	nr	nr	nr	nr	nr	nr	-2	0	-13	7	1	2	5	0	-3	-3	-4	43	5	25	6	8	11
Net	nr	nr	nr	nr	nr	nr	nr	-98	-35	-226	48	58	17	159	46	61	87	139	222	160	313	147	148	225
Non-fossil energy system																								
Process	nr	nr	nr	nr	nr	nr	nr	25	22	21	11	35	40	37	4	7	7	8	98	19	34	8	9	20
En. Cp	nr	nr	nr	nr	nr	nr	nr	-15	-11	0	0	-15	-22	-20	-1	0	0	0	-78	0	-21	0	0	0
LUC	nr	nr	nr	nr	nr	nr	nr	-71	-41	-287	-32	72	66	75	0	37	15	35	435	26	243	79	48	103
Av.Man	nr	nr	nr	nr	nr	nr	nr	22	17	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	nr	nr	nr	nr	nr	nr	nr	-24	-13	-100	-8	-15	1	102	19	-2	38	69	84	1	66	18	13	30
Fertiliz	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UOL	nr	nr	nr	nr	nr	nr	nr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transp.	nr	nr	nr	nr	nr	nr	nr	-2	0	-15	5	0	1	3	-1	-3	-3	-4	40	4	23	6	7	10
Net	nr	nr	nr	nr	nr	nr	nr	-66	-27	-354	-23	77	87	197	21	39	58	107	580	50	346	110	77	163

5. Sensitivity analysis: scenario uncertainty

5.1 Assuming heat utilization equal to 50% of the heat production

Table S36-S39 details the net increase (change, i.e. Δ) in GHG emissions when considering that only 50% of the heat (nominally) produced at the plants is actually used to displace conventional fossil fuels in the district heating network. Table S36-S37 details the results for the scenarios producing 1 kWh bioelectricity in CHP plants (fossil and non-fossil energy system). Table S38-S39 details the results for the scenarios producing 1 MJ bioethanol for transportation (fossil and non-fossil energy system). In both cases, the cells highlighted with grey indicate the scenarios where this change determined that the GHG EF of the scenario became higher than that of the reference fossil fuel. The results for the scenarios producing 1 MJ biomethane for transport are not reported as the effects due to heat recovery are here negligible due to the fact that in these scenarios the biogas is upgraded to biomethane and used for transport.

Table S36. Production of 1 kWh bioelectricity: net increase (Δ compared with baseline) in GHG emissions (g CO_2-eq. kWh^{-1}) following heat utilization equal to 50% of the heat production at the plant. Fossil energy system.

Scenario	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Bel1	325	324	325	326	325	324	324	324	326	324	325	326	325	324	326	324	325	325	325	325	324	325	325	324
Bel2	125	123	123	123	123	122	121	123	123	122	121	123	120	122	120	123	123	122	122	124	123	122	123	122
Bel3	168	197	140	115	170	190	190	165	140	116	115	185	198	159	132	115	115	115	152	115	141	115	115	116
Bel4	109	110	103	126	109	106	109	112	105	127	124	109	110	107	105	110	134	72	107	115	106	125	112	156

Table S37. Production of 1 kWh bioelectricity: net increase (Δ compared with baseline) in GHG emissions (g CO_2-eq. kWh^{-1}) following heat utilization equal to 50% of the heat production at the plant. Non-fossil energy system.

Scenario	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Bel1	98	98	98	99	98	98	98	98	99	98	98	94	129	144	99	98	98	98	98	98	98	98	98	98
Bel2	37	37	37	37	37	37	37	37	37	37	37	83	71	-25	37	37	37	37	37	37	37	37	37	37
Bel3	51	60	42	35	52	57	57	50	42	35	35	85	84	80	40	35	35	35	46	35	43	35	35	35
Bel4	33	33	31	32	33	32	33	34	32	32	32	33	33	32	32	32	33	32	32	31	32	33	33	33

Bel1: Combustion → CHP
Bel2: Syngas → CHP
Bel3: Biogas → CHP. SF → Comb → CHP
Bel4: Biogas → CHP. SF → Syn → CHP

Table S38. Production of 1 MJ bioethanol: net increase (Δ compared with baseline) in GHG emissions (g CO_2-eq. MJ^{-1}) following heat utilization equal to 50% of the heat production at the plant. Fossil energy system.

Scenario	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
BE1	nr	nr	nr	nr	147	52	53	50	36	10	3	44	64	65	7	4	4	6	259	10	68	1	5	1
BE2	nr	nr	nr	nr	120	47	48	41	30	0	0	40	59	54	3	0	0	0	208	0	56	0	0	0
BE3	nr	nr	nr	nr	81	22	24	29	19	8	4	24	32	38	6	4	3	6	150	11	41	-2	6	1
BE4	nr	nr	nr	nr	59	22	22	20	14	-1	0	19	29	27	1	0	0	0	101	1	27	-1	0	0
BE5	nr	nr	nr	nr	nr	nr	nr	41	30	0	0	75	101	155	3	0	0	0	210	0	57	0	0	0
BE6	nr	nr	nr	nr	nr	nr	nr	20	15	0	0	55	71	127	1	0	0	0	102	0	28	0	0	0

Table S39. Production of 1 MJ bioethanol: net increase (Δ compared with baseline) in GHG emissions (g CO_2-eq. MJ^{-1}) following heat utilization equal to 50% of the heat production at the plant. Non-fossil energy system.

Scenario	Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
BE1	nr	nr	nr	nr	43	16	16	15	11	3	1	13	19	19	2	1	1	2	78	3	21	0	2	0
BE2	nr	nr	nr	nr	37	14	14	12	9	0	0	12	18	16	1	0	0	0	63	0	17	0	0	0
BE3	nr	nr	nr	nr	24	9	9	9	6	3	1	7	10	11	2	1	1	2	45	3	12	0	2	0
BE4	nr	nr	nr	nr	18	7	7	6	5	0	0	6	9	8	0	0	0	0	30	0	8	0	0	0
BE5	nr	nr	nr	nr	nr	nr	nr	12	9	0	0	12	18	16	1	0	0	0	64	0	17	0	0	0
BE6	nr	nr	nr	nr	nr	nr	nr	6	4	0	0	6	9	8	0	0	0	0	31	0	8	0	0	0

BE1: C6 → BE. SF → Comb → CHP. Res → Biogas → CHP
BE2: C6 → BE. SF → Comb → CHP. Res → Biogas → CH_4
BE3: C6 → BE. SF → Syn → CHP. Res → Biogas → CHP
BE4: C6 → BE. SF → Syn → CHP. Res → Biogas → CH_4
BE5: C6 → BE. SF → Comb → CHP. Res → Feed
BE6: C6 → BE. SF → Syn → CHP. Res → Feed

5.2 Alternative management of the land → Approach A (with dLUC)

Figure S1 illustrates the two possible approaches for accounting for land use changes, as explained in section 2.3 of the main manuscript. Table S40 details the net change (Δ) when using approach A instead of B.

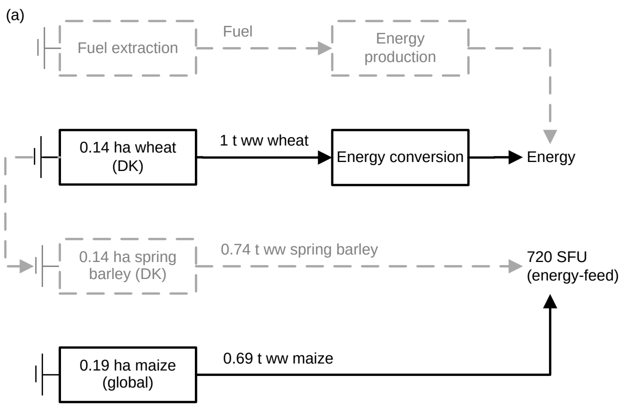

Figure S1. Illustration of the two possible approaches for land use changes: a) including dLUC, b) excluding dLUC.

Table S40. Net change (Δ) in the GHG EFs when using approach A (including dLUC) instead of approach B (disregarding dLUC).

	Unit	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize	Wheat
Per unit of crop	kg CO_2 t^{-1} ww	66	28	10	-71	46	58
Bioelectricity							
Bel1	g CO_2 kWh^{-1}	55	39	46	-324	42	57
Bel2	g CO_2 kWh^{-1}	42	30	35	-246	33	42
Bel3	g CO_2 kWh^{-1}	50	36	33	-266	36	47
Bel4	g CO_2 kWh^{-1}	44	32	33	-261	40	44
Biomethane							
BM1	g CO_2 MJ^{-1}	7	5	5	-41	6	7
BM2	g CO_2 MJ^{-1}	5	4	3	-18	2	3
BM3	g CO_2 MJ^{-1}	5	4	3	-18	2	3
Bioethanol							
BE1	g CO_2 MJ^{-1}	13	11	10	-38	5	7
BE2	g CO_2 MJ^{-1}	13	11	10	-38	5	7
BE3	g CO_2 MJ^{-1}	13	11	10	-38	5	7
BE4	g CO_2 MJ^{-1}	13	11	10	-38	5	7
BE5	g CO_2 MJ^{-1}	13	11	10	-38	5	7
BE6	g CO_2 MJ^{-1}	13	11	10	-38	5	7

5.3 Alternative management of household food waste → Approach A (no import)

Figure S2 illustrates the GHG EFs for household food waste following the approach defined as "A" in the main manuscript: in this, it is assumed that incineration plants will not react to the diversion of organic waste (from incineration to production of bioethanol/biomethane) by importing waste (otherwise disposed of in landfills) from other European countries. This means that the extra (spare) capacity will be decommissioned.

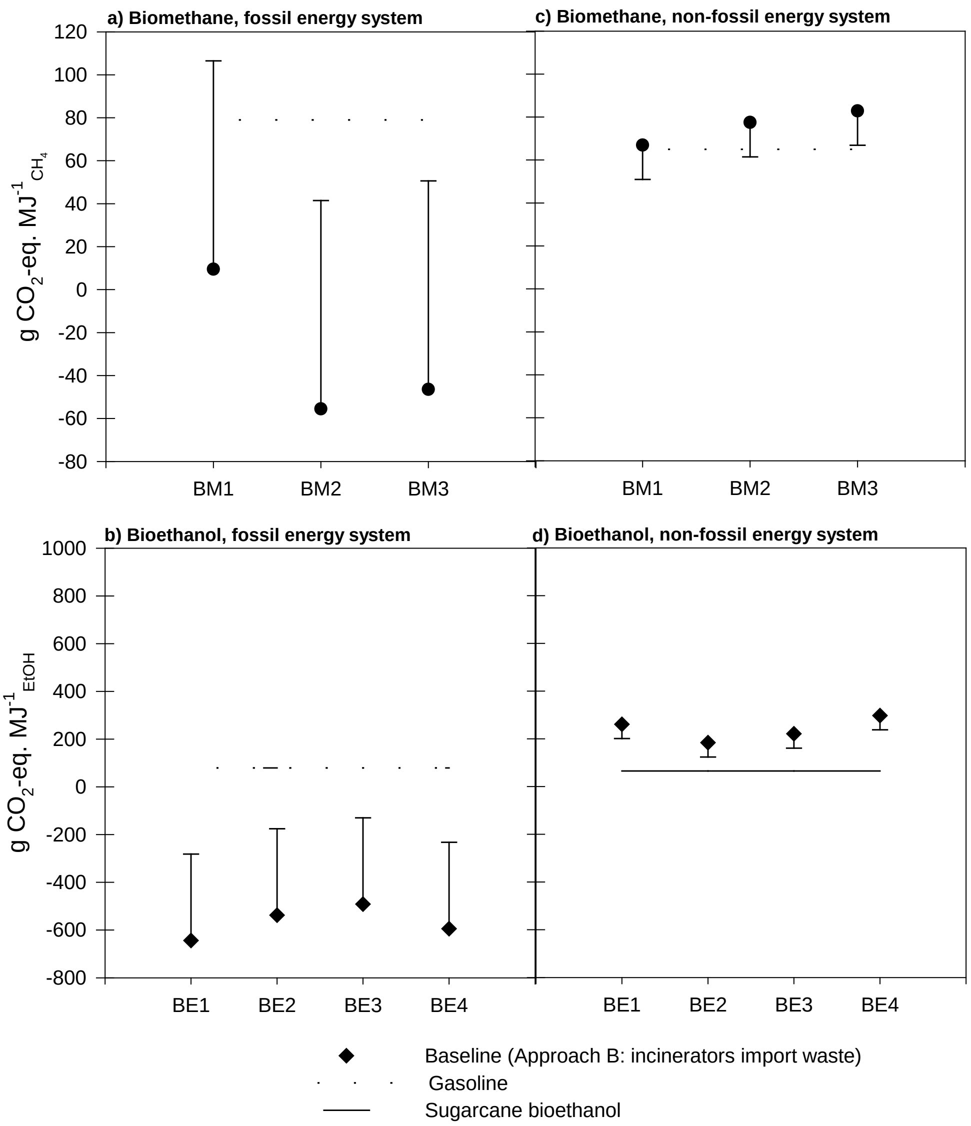

Figure S2. The error bar illustrates the net change (Δ) in the GHG EFs of household food waste under the assumption that incineration plants will not react to the diversion of household food waste from incineration to production of bioethanol/biomethane (they will not import compensatory waste from other EU countries, i.e. the extra capacity will be decommissioned). Scenarios BE5-6 (with fodder as biorefinery co-product) are not applicable to household food waste because of hygienic/technical limitations.

6. Sensitivity analysis: parameters uncertainty

Table S42 (fossil energy system) and Table S43 (non-fossil energy system) presents the results of the uncertainty propagation (Monte Carlo, 1000 simulations) on the parameters used in the model.

Table S41. Uncertainty (σ) around the mean value (μ) quantified by propagating the parameter uncertainties through MonteCarlo simulations; fossil energy system; nr: not relevant.

		Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Bel1	μ	893	308	-212	761	-638	-425	-376	-340	-316	387	1508	-136	-32	812	935	418	617	1051	1011	1468	1589	1317	2183	3942
	σ	60	59	25	63	23	26	22	25	26	36	56	359	268	150	42	85	73	118	62	57	56	98	56	81
Bel2	μ	999	547	155	896	-307	-11	18	51	76	609	1473	207	279	932	1023	634	788	1114	1084	1443	1540	1325	1985	3343
	σ	59	47	27	53	25	29	33	30	34	36	47	195	167	92	36	112	68	97	51	53	53	91	55	66
Bel3	μ	-395	-334	133	-268	nr	-8	27	114	167	89	106	280	244	644	612	661	838	1208	971	1175	1333	1300	1267	1449
	σ	53	56	76	67	nr	53	58	70	60	26	24	292	175	139	41	106	93	120	77	55	69	112	46	35
Bel4	μ	-273	-128	192	-249	-145	190	165	205	237	109	125	373	366	739	660	664	862	1176	983	1187	1339	1316	1272	1497
	σ	51	53	74	67	50	49	51	66	59	26	24	279	165	135	40	106	93	120	74	55	68	112	46	35
BM1	μ	223	151	86	208	9	59	63	68	72	160	306	94	106	213	230	164	190	246	238	295	308	277	387	611
	σ	20	21	14	23	13	15	19	18	18	13	22	120	73	78	16	40	29	42	25	24	23	39	24	27
BM2	μ	-67	-104	40	5	-56	-30	-25	20	46	49	51	30	10	109	108	121	142	184	158	184	212	203	199	218
	σ	23	27	36	26	28	31	37	42	39	18	14	130	82	57	21	50	47	54	34	26	30	49	21	16
BM3	μ	-58	-92	44	5	-46	-17	-14	27	50	49	51	40	24	116	111	121	142	184	164	184	215	203	199	218
	σ	23	27	36	26	28	30	36	42	39	18	14	130	82	57	21	50	47	54	34	26	30	49	21	16
BE1	μ	nr	nr	nr	nr	-639	-77	-64	-97	-41	113	71	18	-31	74	45	87	118	176	324	411	314	254	325	290
	σ	nr	nr	nr	nr	31	78	92	25	27	45	38	142	120	85	16	39	36	45	56	48	34	48	19	16
BE2	μ	nr	nr	nr	nr	-540	-57	-41	-50	-13	158	84	40	-6	129	68	108	138	204	572	460	373	256	350	292
	σ	nr	nr	nr	nr	33	79	95	26	28	42	34	157	122	73	15	40	34	42	51	48	32	47	18	15
BE3	μ	nr	nr	nr	nr	-593	-64	-49	-81	-29	111	72	33	-8	95	45	87	117	176	406	412	340	251	326	290
	σ	nr	nr	nr	nr	32	79	95	25	26	42	34	156	122	73	13	39	34	42	51	48	32	46	18	15
BE4	μ	nr	nr	nr	nr	-492	-40	-25	-33	-1	158	85	55	15	151	68	108	138	204	650	461	399	255	350	292
	σ	nr	nr	nr	nr	34	79	95	25	26	42	34	156	122	73	13	40	34	42	51	48	32	47	18	15
BE5	μ	nr	nr	nr	nr	nr	nr	nr	-115	-49	-226	48	43	-6	137	46	61	87	139	140	160	288	147	148	225
	σ	nr	nr	nr	nr	nr	nr	nr	26	27	48	35	157	122	73	15	50	46	51	51	51	32	53	23	16
BE6	μ	nr	nr	nr	nr	nr	nr	nr	-98	-35	-226	48	58	17	159	46	61	87	139	222	160	313	147	148	225
	σ	nr	nr	nr	nr	nr	nr	nr	25	26	48	35	156	122	73	13	50	46	51	51	51	32	53	23	16

Table S42. Uncertainty (σ) around the mean value (μ) quantified by propagating the parameter uncertainties through MonteCarlo simulations; non-fossil energy system; nr: not relevant.

		Slurry pig manure	Slurry cow manure	Chicken manure	Sewage sludge	HH food waste	Garden waste	Wood residues	Wheat straw	Maize stover	Wild grass	Seaweed	*Miscanthus*	Willow	Ryegrass	Sugar beet	Maize grain	Wheat grain	Barley grain	Brewer's grain	Beet pulp	Beet top	Beet molasses	Potato pulp	Whey
Bel1	μ	-175	-264	-134	47	94	-230	-156	-107	-104	119	405	107	132	632	602	637	832	1266	976	1306	1364	1476	1624	2337
	σ	26	30	13	27	5	12	10	7	8	10	18	238	200	111	20	89	67	108	51	52	57	102	44	39
Bel2	μ	-57	-126	-25	113	364	-99	-43	-5	-2	166	384	160	176	562	533	566	715	1042	827	1080	1125	1202	1322	1876
	σ	26	27	13	21	7	13	10	10	10	10	16	238	128	92	18	91	59	94	44	44	49	89	40	32
Bel3	μ	-511	-419	1	-216	nr	-74	-25	38	53	36	24	229	213	549	460	629	806	1176	897	1129	1182	1267	1208	1361
	σ	46	50	65	61	nr	24	24	28	30	17	22	302	190	114	24	101	84	115	68	53	59	110	43	33
Bel4	μ	-463	-313	16	-208	428	-10	17	63	76	44	26	238	230	575	469	620	823	1131	856	1125	1151	1275	1203	1398
	σ	45	47	64	61	39	23	23	27	30	17	22	288	180	111	23	101	85	115	66	53	58	110	43	33
BM1	μ	4	-7	10	33	67	-2	7	13	14	42	79	40	43	106	102	107	132	187	150	190	196	211	231	322
	σ	10	12	11	11	13	12	16	17	15	9	7	100	61	46	11	37	28	37	21	21	19	41	17	14
BM2	μ	-72	-74	9	-15	82	-5	4	16	18	16	14	52	53	98	71	91	111	153	145	151	180	172	164	181
	σ	21	25	34	25	22	25	31	34	36	19	14	134	89	48	18	51	46	52	33	26	28	50	21	15
BM3	μ	-67	-65	12	-15	87	3	12	21	21	16	14	59	62	102	73	91	111	153	149	151	183	172	164	181
	σ	21	25	34	25	25	25	31	33	35	18	14	134	89	48	18	50	45	52	32	26	27	50	21	15
BE1	μ	nr	nr	nr	nr	262	-7	11	16	18	59	20	77	82	208	65	100	124	191	1089	381	448	227	294	235
	σ	nr	nr	nr	nr	21	54	56	17	22	22	15	167	101	71	13	39	33	43	39	27	32	48	17	14
BE2	μ	nr	nr	nr	nr	191	-26	-7	-18	-3	24	10	60	66	169	49	83	107	170	920	344	406	218	276	229
	σ	nr	nr	nr	nr	35	54	56	18	22	23	15	167	101	72	13	39	33	43	41	27	32	48	17	14
BE3	μ	nr	nr	nr	nr	298	6	25	29	27	58	20	88	100	224	66	100	124	192	1146	381	465	224	295	234
	σ	nr	nr	nr	nr	33	54	56	17	21	22	15	167	101	71	12	39	33	43	39	27	32	48	17	14
BE4	μ	nr	nr	nr	nr	228	-12	8	-6	7	23	10	72	83	185	50	83	107	170	978	344	423	218	276	229
	σ	nr	nr	nr	nr	35	54	56	18	22	23	15	167	101	72	12	39	33	43	41	27	32	48	17	14
BE5	μ	nr	nr	nr	nr	nr	nr	nr	-78	-36	-354	-23	65	69	181	21	39	58	107	517	50	329	110	77	163
	σ	nr	nr	nr	nr	nr	nr	nr	17	22	33	17	167	101	71	13	49	46	52	40	32	32	54	21	16
BE6	μ	nr	nr	nr	nr	nr	nr	nr	-66	-27	-354	-23	77	87	197	21	39	58	107	580	50	346	110	77	163
	σ	nr	nr	nr	nr	nr	nr	nr	17	22	33	17	167	101	71	12	49	46	52	40	32	32	54	21	16

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